THE LEGACIES
OF
EDWIN HOWARD ARMSTRONG

MAJOR EDWIN HOWARD ARMSTRONG

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THE LEGACIES
OF
EDWIN HOWARD ARMSTRONG

The Regenerative Circuit

The Superheterodyne Circuit

The Superregenerative Circuit

Frequency Modulation

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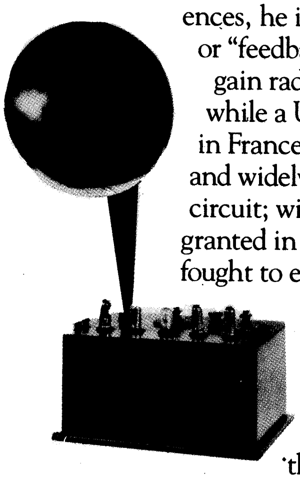
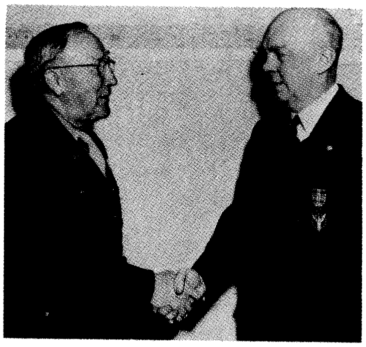
EDWIN HOWARD ARMSTRONG

One extraordinary man did more to advance the art of radio and telecommunications than any other human being. This important, but little-known, American inventor was Columbia University Professor Edwin Howard Armstrong, known by friends as "the Major."



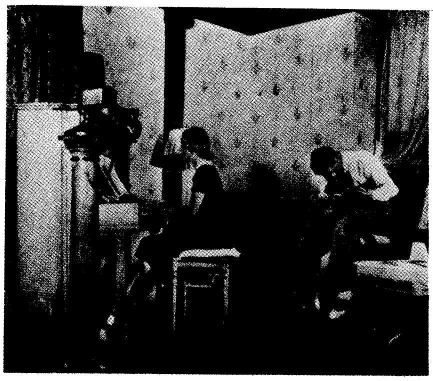
Armstrong's list of accomplishments is astonishing: as an undergraduate at Columbia's School of Engineering and Applied Sciences, he invented the regenerative, or "feedback" circuit, the first high gain radio frequency amplifier; while a U.S. Signal Corps captain in France, he invented the versatile and widely used superheterodyne circuit; with his four FM patents, granted in 1933, he developed, and fought to establish, wide band frequency modulation, later selected by the Federal Communications Commission to transmit TV's sound. All told, "the Major" was granted forty-two historic patents, and presented as many substantive and distinguished scientific papers.

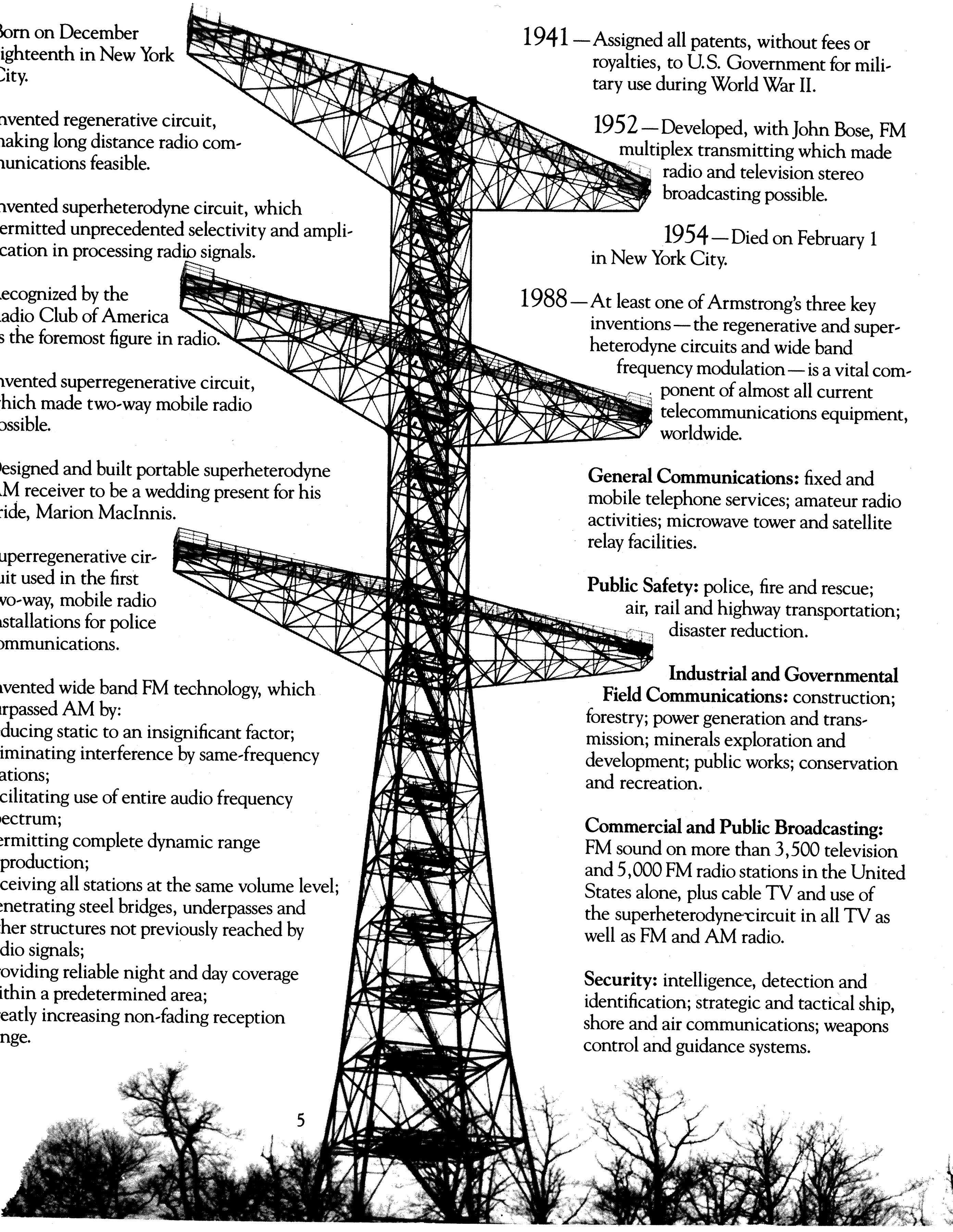
Throughout the remainder of his life, Edwin Armstrong worked to advance FM radio technology. He demonstrated how more than one signal could be carried on a single FM channel. This feat became known as multiplexing and led to both FM and TV stereo broadcasting as well as other commercial services.



When the United States entered World War II, "the Major" came to his country's aid by allowing it free use of his many patents for the duration. That generous and patriotic act led to the development of advanced electronic communications, recognition, guidance and detection systems, which helped the United States and its Allies immeasurably in winning the war.

To comprehend the importance of Edwin Armstrong's work, it must be recognized that the fields of commercial and public radio and TV broadcasting are only a few of many through which his inventions combine to serve mankind. The most significant events in his life and work are presented in the following chronological compilation.





1890 — Born on December eighteenth in New York City.

1912 — Invented regenerative circuit, making long distance radio communications feasible.

1917 — Invented superheterodyne circuit, which permitted unprecedented selectivity and amplification in processing radio signals.

1919 — Recognized by the Radio Club of America as the foremost figure in radio.

1922 — Invented superregenerative circuit, which made two-way mobile radio possible.

1923 — Designed and built portable superheterodyne AM receiver to be a wedding present for his bride, Marion MacInnis.

1932 — Superregenerative circuit used in the first two-way, mobile radio installations for police communications.

1933 — Invented wide band FM technology, which surpassed AM by:
- reducing static to an insignificant factor;
- eliminating interference by same-frequency stations;
- facilitating use of entire audio frequency spectrum;
- permitting complete dynamic range reproduction;
- receiving all stations at the same volume level;
- penetrating steel bridges, underpasses and other structures not previously reached by radio signals;
- providing reliable night and day coverage within a predetermined area;
- greatly increasing non-fading reception range.

1941 — Assigned all patents, without fees or royalties, to U.S. Government for military use during World War II.

1952 — Developed, with John Bose, FM multiplex transmitting which made radio and television stereo broadcasting possible.

1954 — Died on February 1 in New York City.

1988 — At least one of Armstrong's three key inventions — the regenerative and superheterodyne circuits and wide band frequency modulation — is a vital component of almost all current telecommunications equipment, worldwide.

General Communications: fixed and mobile telephone services; amateur radio activities; microwave tower and satellite relay facilities.

Public Safety: police, fire and rescue; air, rail and highway transportation; disaster reduction.

Industrial and Governmental Field Communications: construction; forestry; power generation and transmission; minerals exploration and development; public works; conservation and recreation.

Commercial and Public Broadcasting: FM sound on more than 3,500 television and 5,000 FM radio stations in the United States alone, plus cable TV and use of the superheterodyne circuit in all TV as well as FM and AM radio.

Security: intelligence, detection and identification; strategic and tactical ship, shore and air communications; weapons control and guidance systems.

ARMSTRONG, Edwin H(oward), elec. engr.; b. New York, N.Y., Dec. 18, 1890; s. John and Emily Gertrude (Smith) A.; E.E. Columbia, 1913, Sc.D. 1929; Sc.D. Muhlenberg College, 1941; married Marian MacInnis, December 1, 1923. Assistant in dept. elec. engring., Columbia, 1913-14; asso. with Prof. Michael I. Pupin in research, Marcellus Hartley Research Lab. at Columbia U., 1914-35; prof. of elec. engring., Columbia, since 1934. Served as capt. and major, Signal Corps, with A.E.F., 1917-19. Chevalier, Legion d'honneur, 1919. Awards: Medal of Honor, Inst. of Radio Engrs., 1917; Egleston medal, Columbia U., 1939; "Modern Pioneer" plaque, Nat. Assn. Mfrs. 1940; Holley medal, Am. Soc. Mech. Engrs., 1940; Franklin medal, Franklin Inst., 1941; John Scott medal, Bd. of City Trusts, City of Phila., 1941; Edison medal, Am. Inst. of Elec. Engrs., 1943; award to be known as Armstrong Medal, established by Radio Club of America, 1935; Medal for Merit, 1947; Washinton award for 1951, Western Soc. Engrs. Mem. Institute Radio Engrs. Rep. Presbyn. Contributor to tech. jours. Inventions: regenerative circuit, 1912; superheterodyne, 1918; super-regenerative circuit, 1920; method of eliminating static by means of frequency modulation, 1939. Home: 435 E. 52nd St., N.Y. City. Died Feb. 1, 1954; buried Locust Grove Cemetery, Merrimack, Mass.

1890 - EDWIN HOWARD ARMSTRONG - 1954

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AN INTRODUCTION

by **John D. Ryder, Ph.D. (F), and Donald G. Fink (LF)**

Excerpted from *Engineers & Electrons*, 1944 IEEE Press

Armstrong's First Invention: The Regenerative Circuit

About 1913, Edwin Armstrong of Columbia University had evolved the regenerative circuit using positive feedback from the output circuit of a radio detector to the input circuit. Since this connection effectively increased the input signal, amplification was increased many times. Perhaps the fundamental of Armstrong's invention was his realization that some of the high-frequency input signal existed in the plate circuit and could be fed back, a realization beyond the common view that after detection, only audio frequencies were present. Such regenerative circuits were in fact oscillators, that is, generators of high frequencies, but they were operated at a critical point just short of oscillation. The circuit, which required some skill from the operator, was used until the 1930's, providing a means of truly long-distance communication.

At about the same time, Reginald Fessenden, Alexander Meissner in Germany, and H.J. Round in England all originated circuits giving somewhat similar results. A year or so later deForest also made similar claims. A patent action was started by deForest and later taken over by AT&T, which led to a long legal battle not based on the technical facts and exhausted Armstrong's finances. Finally, the Supreme Court in 1934 decided against Armstrong. The Board of Directors of the Institute of Radio Engineers (IRE) took notice of this injustice, and publicly reaffirmed its 1918 action in awarding to Armstrong the IRE Medal of Honor for his "achievements in relation to regeneration and the generation of oscillations by vacuum tubes." Because of patent litigation, many companies had used the regenerative circuit without awarding Armstrong his royalties. The greatest use of the circuit occurred in the 1920's when the Armstrong circuit received major acclaim.

Armstrong's Second Invention: The Superheterodyne

In 1918, Edwin Armstrong again appeared on the scene. While attached to the U.S. Signal Corps laboratories in Paris, he developed a receiving circuit even more important than the regenerative circuit -- the superheterodyne. Fessenden, in 1901, had proposed a reception method which he called the heterodyne. This name from the Greek heteros (external) and dynamis (force). He used a steady signal generated in the receiver, mixing this with the received signal. From this process appeared a third frequency equal to the difference between the first two frequencies. If the difference was small enough to lie in the audible range (200 Hz - 10kHz), the modulation or variation of the incoming signal could be heard in the headphones. The method was not widely accepted because the local oscillators that generated the constant signal were not sufficiently stable.

What Armstrong invented was a great improvement on the heterodyne, justifying the name superheterodyne. It, too, used a local oscillator frequency, mixed this with the incoming signal to produce a much lower (but not yet audible) intermediate frequency (IF). This intermediate frequency was then amplified at the lower frequency and great selectivity between signals could be achieved in the tuned circuits attached to these lower frequency amplifiers. The local oscillator frequency had only to be stable enough to place the intermediate signal in the frequency band passed by the amplifiers. Thus, Armstrong overcame the limitation of the heterodyne method. After much amplification in such IF amplifiers, detection followed to make the signal audible. A very considerable increase in overall amplification was possible with this receiver, and today it is the circuit universally used in almost all radio, television, and communication receivers.

This was Armstrong's second great invention, one from which he would receive some financial reward. Two others, superregeneration and the use of frequency modulation, were to follow.

Simple receivers and transmitters with crystal or diode detectors and audio amplifiers were used on the ground and in the air in World War I. Except for Armstrong's superheterodyne, which was not put into production until 1924, there was little improvement in the circuits used. However, industry learned how to produce vacuum tubes in quantity, production of one type approaching one million a year. These tubes had to yield reproducible results when placed in receivers and transmitters, and standardization of construction was difficult.

In 1920, Armstrong sold his regenerative-circuit and superheterodyne patents to Westinghouse for $335,000, which helped him to meet the legal bills he was incurring as the deForest suit on regeneration dragged on. Armstrong retained a right to license his regenerative detector circuit for "amateur and experimenter" use and this brought him some royalties.

Armstrong and Superregeneration

At about this time, Armstrong announced his third invention, by which regeneration was carried to an extreme and one tube could produce an output directly to the loudspeaker. He called it "superregeneration." As a business policy, RCA refused to pay royalties and therefore had been excluded from the use of the (Hazeltine) Neutrodyne circuit. Seeing the need for a new circuit to boost receiver sales, Sarnoff was interested in Armstrong's new invention. For the first time, Armstrong prepared well for negotiations. For the superregeneration patents he received $200,000 and 60,000 shares of RCA stock; the stock was later to make him wealthy.

However, the superregenerative circuit lacked selectivity needed for the crowded broadcast frequencies. This made it suitable only for wide-band high-frequency channels. The invention was used for "identification of friend from foe" circuits during World War II. Otherwise it remains on the shelf, awaiting some new application.

Armstrong and Frequency Modulation

Edwin Armstrong had another surprise for the field in the 1930's. He developed a way to exploit a new approach to signal modulation -- frequency modulation (FM). Radio signals must be of high frequency in order to radiate efficiently; music and speech occur at the much lower frequencies, below 15kHz. In the broadcast signal, the music and radio frequency must be joined; that is, the radio frequency is varied (modulated) by the audio frequencies. This variation can occur in any of three carrier wave parameters: amplitude, frequency, or phase. The easiest form of modulation is to alter the carrier wave's power (amplitude), so the radio pioneers had chosen amplitude modulation (AM). In AM, the strength of the related signal is dependent instant by instant on the amplitude of the audio signal. FM had been neglected as an alternative; in fact, it had been unjustly condemned.

In 1922, there were over 300 broadcast stations jammed into a narrow frequency band, and a search was on for a method to narrow the frequency band taken by each station. In AM, the band is twice the range covered by the original speech or music. In practice, this is limited to plus-or-minus 5 kHz on each side of the center or carrier frequency. In 1922, John R. Carson of the Bell engineering group wrote an IRE paper that discussed modulation mathematically. He showed that FM could not reduce the station bandwidth to less than twice the frequency range of the audio signal. Since FM could not be used to narrow the transmitted band, it was not useful. Thus was the kiss of death given to FM.

Actually, Carson had reasoned only that narrow-band FM would distort. Armstrong took the opposite view and expanded the signal bandwidth to 200 kHz and found a useful result. But in 1935, when many hundreds of broadcast stations were jammed into a 1000-kHz band, any proposal to use more spectrum space for each station was heresy. Use of a 200-kHz channel called for moving to higher frequencies, and Armstrong took his experiments to 41 MHz.

Two problems that had been with radio from the beginning were atmospheric static and man-made electrical noise. This interference contained large variations in signal amplitude. Armstrong proposed that frequency variations should carry the useful signal. Amplitude variations could then be stripped off the FM signal, largely eliminating noise and static. Reception highly faithful to the input signal was to be expected. The era of "high fidelity" had dawned.

A circuit was needed to vary the frequency of the transmitter in accordance with the microphone's audio signal. The transmitter could operate constantly at peak output, that is, no reserve of power was needed as in AM, in which a 25-kW broadcast signal requires a transmitter capable of reaching 100-kW on peaks. Fm required a "limiter" to strip off all amplitude noise in the receiver and a detector to convert frequency variation into amplitude variation. This would make the signal ready for audio amplification and the loudspeaker.

This system was built by Armstrong on tables in a basement at Columbia University and demonstrated to Sarnoff in late 1933; Armstrong had agreed to give RCA first chance at future inventions. Field tests ensued, with a transmitter on the Empire State Building. These showed freedom from interference to a range of 125 km (80 mi). FM was the topic of a paper and demonstration by Armstrong before the IRE in New York, but nor until 1935 (the field tests were the reason for the delay in presenting the paper).

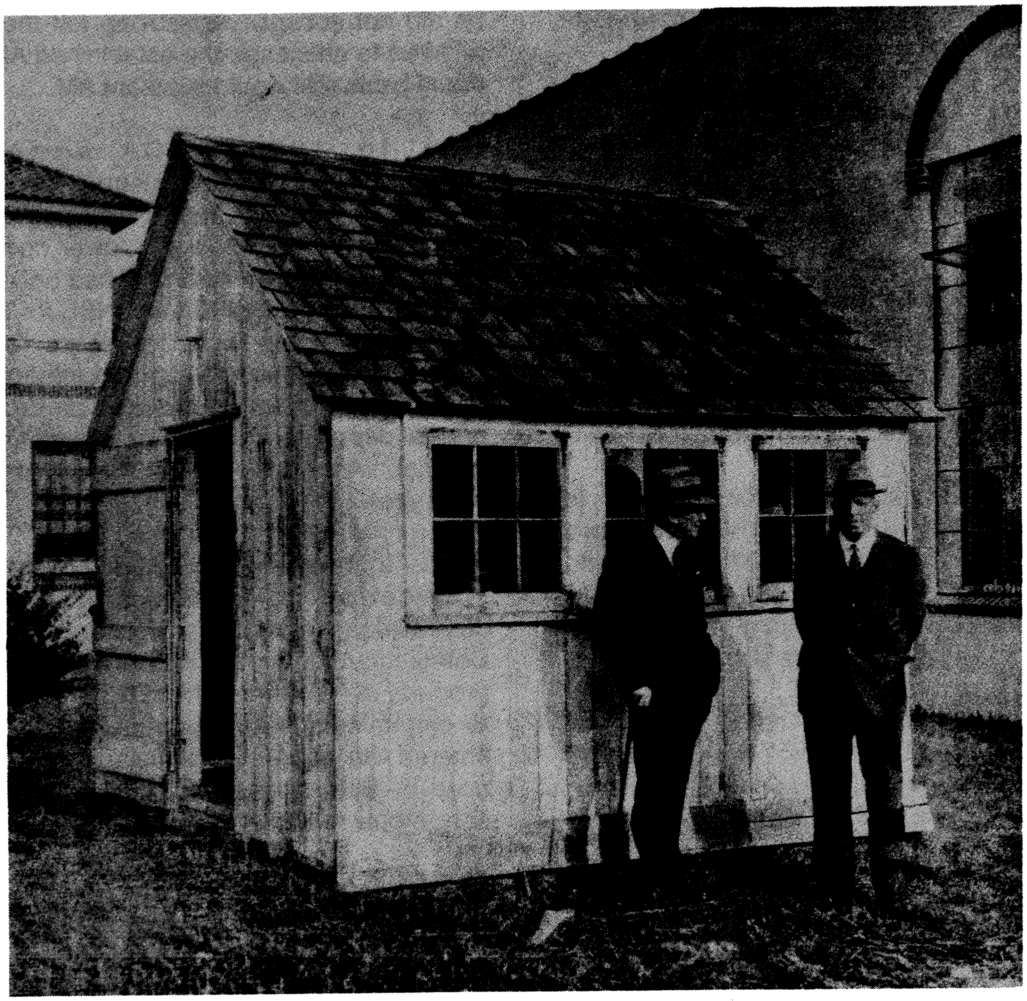
Armstrong Battles For His Life - and Loses

During the next years, Armstrong battled to improve his system and to sell it. In 1938, General Electric asked for a license to produce equipment under the FM patents. This action showed the influence of W.R.G. Baker, head of G.E.'s electronics department, who was enthusiastic about FM. Armstrong's own experimental station at Alpine, NJ, went on the air in 1938, after an expenditure of $300,000. A network of New England FM stations developed (the Yankee Network), which was used relays located on mountain tops. Later, the sound channel of the television signal was transmitted by FM. RCA remained aloof, protecting its investment in AM stations and networks. In 1940, RCA made an offer to Armstrong for a royalty-free license for FM, which he did not accept. Armstrong felt that if FM were allowed to challenge the established AM field on an equal basis, FM would supplant AM.

In 1946, RCA announced a limiter-discriminator circuit to circumvent Armstrong's patents, but it was a circuit in which quality was subordinated to lower cost. By 1949, when the basic patents on FM had only two years to run, Armstrong sued RCA and NBC for infringement. This suit was based on his desire to protect his invention from cost-cutting and inferior design, as he saw it. The suit was to drag on for five years of pretrial depositions and cross-examination, much of it trivial. Armstrong was in the witness chair for a solid year.

In the meantime, FM had triumphed with its application to police and mobile radio communication by Daniel Noble of the University of Connecticut. In mobile radio, the noise-combatting property of FM was a critical benefit. Noble went on to employment with Motorola, and that company entered the mobile radio field. In 1939, FM was used by Bell Laboratories in a radio altimeter that used signal reflections from the surface of the earth.

RCA proposed a settlement of the suit under terms which Armstrong again rejected in late 1953. In that winter Armstrong apparently suffered a brain ailment, and his financial resources were drained by the Alpine station and his legal fees, but the suit dragged on. His attorneys assured him that a settlement with RCA could be reached, but he was pessimistic. His disturbed mental attitude brought an estrangement from his wife, whom he had met when she was Sarnoff's secretary in 1923. On the night of January 31, 1954, he wrote a letter to his wife. Dressed in hat, overcoat, scarf, and gloves, his body was discovered the next morning on the roof of a third-floor extension of his apartment building in New York.



"Babylon Shack" after it had been moved to RCA site at Rocky Point, New York, 1933. Guglielmo Marconi (left) and Major Edwin Howard Armstrong. This wireless shack was constructed in 1902 for Marconi Co. and was later bought by Armstrong. It was presented to David Sarnoff when he was president of RCA. Marshall Etter, the last engineer in charge of RCA Rocky Point Station, has researched the history of the Babylon wireless shack.

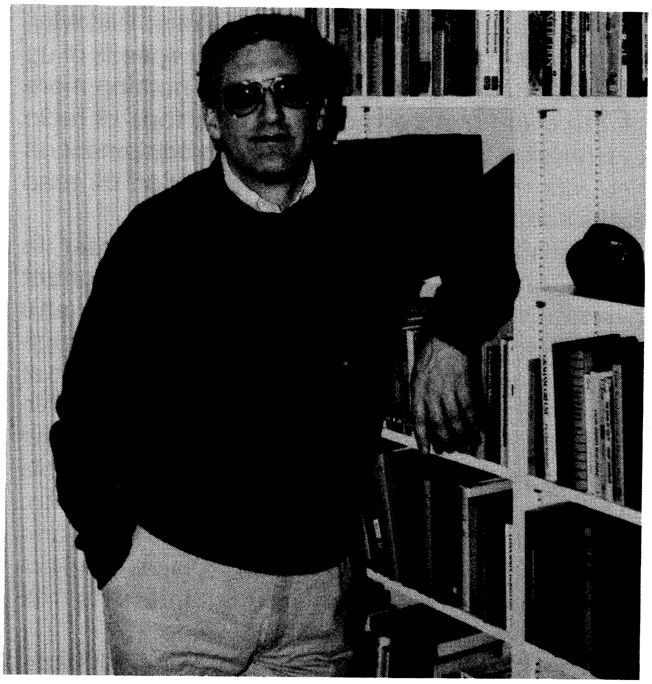
Courtesy of Harold Beverage

RADIO REVOLUTIONARY

Edwin Armstrong's innovations, culminating in the introduction of FM, made modern broadcasting possible, but his life ended in tragedy.

by Thomas S. W. Lewis, Ph.D. (M)

Originally published in *American Heritage of Invention & Technology* 1, No. 2,(Fall 1985): 34-41.



Just before Christmas in 1913 three engineers from the American Marconi Company crowded into a cluttered basement room in Philosophy Hall at Columbia University to see a young man demonstrate his new invention, a regenerative, or feedback, circuit, which he confidently declared had made possible the most effective wireless receiver in the world. This was a time of extravagant claims -- and not a little fraud -- about the new technology coming to be called radio, and the visitors were suspicious as they heard a wireless telegraph transmission from the Marconi company's station three thousand miles away in Clifden, Ireland, a station normally picked up with great difficulty in the eastern United States. That inventor, a recent graduate of Columbia named Edwin Howard Armstrong, had hidden the receiver in a black box which made the listeners all the more skeptical. But a few days later, after confirming the authenticity of the messages, the assistant chief engineer of the party, a young man named David Sarnoff, declared the invention "the most remarkable receiving system in existence." This occasion marked the first meeting of Armstrong and Sarnoff, men who were to become two of the most important figures in radio. Each was to have a profound influence upon the other when their careers became intertwined.

The history of radio in the United States is one of strong and often eccentric personalities. Armstrong, as one friend described him, was "all focused in one direction." Son of the American representative of the Oxford University Press, he was born in 1890 and grew up in Yonkers, New York. At the age of fifteen, after reading a copy of *The Boy's Book of Inventions*, he declared his intention of becoming an inventor in the field of radio. Soon he had filled his attic bedroom with coils, coherers, crystals, Leyden jars, and condensers, and he busied himself experimenting with electrical circuits. In the still of the night, when signals were clearest, he listened to faint sounds from transmitters as far away as Key West. In 1910 he erected single-handedly a 125 foot vertical antenna in his yard.

Almost nobody at the turn of the century had the prescience to understand the potential of a technology so new, imprecise, and as yet unsophisticated as radio. It seemed more a hobby for amateurs than a serious commercial venture. Transmissions were limited to laboratory demonstrations or experimental efforts over distances of less than two hundred miles. Wireless communications had begun only a few years before: Heinrich Hertz had successfully transmitted electromagnetic waves across a room in the late 1880s; Guglielmo Marconi had sent his first wireless message across the Atlantic in 1901, an accomplishment that was shortly understood to be partly due to the reflection of radio signals off the upper atmosphere -- a discovery that was crucial to all later work in radio. With the hope of increasing the capability of wireless receivers, Lee De Forest was developing the first three-element vacuum, or audion, tube at the very time Young Armstrong was reading tales of great inventors.

Aside from radio, Armstrong developed few passions: tennis, fast cars, and high places. Tennis he played whenever he could, spending hours charging his barrel-chested six-foot frame about the court. To indulge his craving for speed, he would travel to the private Long Island Motor Parkway, where for the fee of a dollar he drove at speeds of up to a hundred miles an hour. He liked nothing more than to climb hundreds of feet to the tops of radio transmission towers or to install radio equipment on the roofs of tall buildings. For relaxation he read books about mountaineers.

Armstrong's stubbornness and interest in difficult problems led him to his most important inventions. He realized that receivers and transmitters might benefit from radical design changes, and he challenged virtually every fact of radio technology that others accepted. As his technical papers reveal, he enjoyed showing up the experts, be they eminent professors at Columbia University, where he studied electrical engineering; mathematicians, whose elegant solutions and theorems he inherently distrusted; or, later, heads of corporations whose commercial interests ran counter to what he was trying to develop.

The idea for the regenerative, or feedback, circuit came to Armstrong in a moment of revelation while he was mountain climbing in Vermont in 1912, between his junior and senior years at Columbia. Upon his return to the university he built the circuit and thereby greatly enhanced De Forest's audion as a detector for wireless signals.

Resembling a small light bulb fitted with a grid placed between the filament and a metal plate, De Forest's 1906 audion tube had helped amplify a radio signal but did little else; a half dozen years later the inventor was still struggling to make the tube practical. Understanding the tube's capability even better than De Forest did, Armstrong found that by looping the signal from the audion plate circuit back to the grid via suitable coupling coils, he could increase amplification enormously. And when he increased the feedback beyond a critical level, the tube became a transmitter.

Inventing his regenerative circuit proved to be easier than having it accepted commercially, at least before broadcasting became a business. American Marconi and the Atlantic Communication Company bought the right to use it in limited applications; licensing the invention to smaller manufacturers proved more profitable. By 1922 the inventor had issued twenty-four licenses, and royalties reached some ten thousand dollars a month.

The idea for Armstrong's second major invention came to him in another moment of insight, while he was stationed in France as a captain in the Army Signal Corps during World War I. Watching a German bombing raid, he pondered a way of locating the positions of airplanes by tracking the weak high-frequency waves emitted by the engines' ignition systems. He envisioned a superheterodyne receiver, based on the electrical mixing of frequencies. The technique of mixing frequencies had been introduced to radio technology by the Canadian engineer Reginald Fessenden in about 1903. It was Armstrong, however, who developed its commercial practicality.

In the superheterodyne the incoming signal is mixed, or heterodyned, with the steady output of a local oscillator to produce a signal of intermediate frequency that can be much more cleanly and effectively amplified. Armstrong's laboratory constructed an eight-tube receiver which included three intermediate frequency amplifiers, a detector for converting the signal to an audio frequency current, and two audio frequency amplifiers. Over the next few years Armstrong designed some very elegant devices using this circuitry to achieve improved sensitivity and selectivity.

By the mid-1920s the regenerative receiver and crystal sets began to decline in popularity as the transitional Neutrodyne receiver and its variations came on the market with better fidelity and amplifications; after 1930 there was wide-spread adoption of the "superhet" as wider patent licensing became available and it became easier to tune -- with a single dial -- than its predecessors. Today the superheterodyne constitutes the basic receiver in practically every radio.

When Armstrong returned to the United States after World War I, nearly everyone recognized him as foremost in his field. The Radio Club of America gave a dinner in his honor at New York's Hotel Ansonia in 1919. His large, melon shaped head, which had been prematurely balding before the war, had been made into a complete dome by an anthrax infection contracted in France; his firm mouth, long upper lid, and blue eyes, his modest and laconic speech, and the occasional involuntary twitch of his neck and shoulders (a reminder of a bout with chorea in childhood) remained unchanged.

Not all thought him pre-eminent, however. Lee DeForest had claimed the prior invention of the regenerative circuit, and now he was eager to press his suit. The litigation quickly became acrimonious, taking up much of Armstrong's time and energy until its resolution years later, and it helped determine his bitter attitude toward patent law. Fees for his defense lawyers began to force him into debt, and when, in 1920, the Westinghouse company offered him $335,000 for exclusive rights to the regenerative and superheterodyne circuits, Armstrong decided to sell. The sum was substantial; even after paying his creditors, Armstrong was now wealthy.

Armstrong's next invention, the superregenerative circuit, made him a millionaire. He developed it as a consequence of his litigation with DeForest. When preparing his regeneration apparatus for a demonstration to the court in 1922, Armstrong said, he "accidentally ran into the phenomenon." The superregenerative circuit greatly improved the feedback process (although the device would not become fully practical for another decade). The Radio Corporation of America paid Armstrong $200,000 in cash and sixty thousand shares of stock for the invention. Later the corporation added twenty thousand shares for consulting work, making Armstrong the largest stockholder in the company. Just before the stock market crash of 1929 Armstrong sold most of his stock for $114 a share.

Armstrong's association with RCA drew him close to the corporation's president, David Sarnoff, and even closer to Sarnoff's tall, charming, and intelligent secretary, Marion MacInnis. He courted her in the manner of the twenties, taking her for drives on the Motor Parkway in a new Hispano-Suiza, on trips up the Hudson, and to dinner and theater parties. Perhaps it was this growing relationship that inspired Armstrong to perform his most daring stunt. On a May afternoon in 1923 he scaled the transmitting tower of RCA's station WJZ, 450 feet above Forty-second Street. Hanging over the street from one of the aerial's crossbeams, he posed for a photographer he had brought along. That evening he returned to stand atop the large banded iron ball crowning the tower. Sarnoff was not amused, and for a while he barred Armstrong from his offices. Marion MacInnis married Armstrong in December. For their honeymoon, they traveled in the Hispano-Suiza to Florida. His wedding present to his bride was the first portable superheterodyne radio -- a huge mechanism that they lugged onto the beach with them.

Early in 1924 Armstrong returned to Columbia to continue an effort he had begun a decade earlier to eliminate static from radio. Conventional wisdom held the problem insoluble. "Static, like the poor, will always be with us," the chief engineer of AT & T had declared. But Armstrong labored persistently, sometimes taking several months to set up an experiment that involved as many as a hundred vacuum tubes. He worked a seven-day week and usually a fifteen-hour day, broken only by a lunch of a sandwich and a glass of milk. Though he held a chair of electrical engineering at Columbia, he taught no courses. His salary was one dollar a year.

Shortly before Christmas 1933 David Sarnoff returned to the same cluttered basement room of Philosophy Hall where twenty years earlier he had witnessed Armstrong's demonstration of the regenerative circuit. Armstrong and Sarnoff had become friends,. but not intimate ones. Armstrong was tall, slow-speaking, cerebral, and gentle; Sarnoff was short, talkative, and aggressive. Armstrong's background was middle-class, Presbyterian, and American; Sarnoff's, lower-class, Jewish, and Russian. In 1906 Sarnoff had become an office boy for the Marconi company. From that position he had risen steadily to telegraph operator, station manager, and assistant chief engineer. The enterprising Sarnoff had become the self-appointed spokesman for and prophet of radio as a mass medium. When RCA was formed in 1919, he quickly assumed a leading role; by 1930, he was president.

Armstrong had called Sarnoff to witness a demonstration of his invention to eliminate static from radio. Sarnoff had long expressed the hope that an inventor would come forth with a "little black box" to do just that. What he found was not a simple device to be added to existing radios or transmitters, but an entirely new radio system: frequency modulation, or FM.

In the previous decade radio had become a major presence across the country. The number of homes with radios in 1922 stood at 60,000, with many of these radios home-built; by the Depression years of 1933, when Franklin Roosevelt broadcast his first fireside chat, the number was 19,250,000.

Automobile radios were first introduced in 1930 and numbered 500,000 three years later. The use of Armstrong's superheterodyne circuitry in receivers had grown rapidly. When people were not listening to the President, they were hearing shows with stars like Amos and Andy, Ted Mack, Fred Allen, and Bob Hope. On Broadway, Cole Porter acknowledged radio's importance in a song:

> *Just think of those shocks you've got*
> *And those knocks you've got*
> *And those blues you've got*
> *From the news you've got*
> *And the pains you've got*
> *(If any brains you've got)*
> *From those little radios.*

All "those little radios" worked on the principle of amplitude modulation. The invention that Armstrong demonstrated to Sarnoff, however, introduced some fundamental changes. *Modulation* refers to the way in which voice and music information is impressed on a radio wave. In amplitude modulation (AM) the information signal varies the amplitude of the wave; what Armstrong proposed was a method of modulation that would vary the wave's frequency. By analogy to waves of water, AM imparted the signal through changes in the heights of the waves; FM did so by varying the spacing of the wave crests. Since most noise affected wave height, or amplitude, much more than frequency, FM was much less vulnerable to interference. But FM would require new transmitters and receivers and would need a fairly wide channel spacing -- up to two hundred kilohertz -- space for which was not readily available in the already crowded five hundred to sixteen hundred kilohertz AM band. The inventor proposed VHF (very high frequency) allocations, where plenty of room was available. It was in this part of the spectrum, furthermore, that FM's promise of improved high fidelity might best be fulfilled.

Sarnoff was presented with an enormous dilemma. The industry had a considerable investment in medium-band AM, and a move simply to abandon it and switch to VHF FM seemed financially disastrous. It clearly represented a major threat to any company already committed to AM. Sarnoff hoped for some sort of compromise, though, and was not averse to a little experimenting. In March 1934, therefore, Armstrong's equipment was moved to the top of the Empire State Building for definitive broadcasting tests. Receiving sites were set up first at Westhampton Beach, Long Island, New York, and then at Haddonfield, New Jersey.

What the experimenters showed was a truly substantial improvement in the signal-to-noise ratio with the new technique. An FM signal twice as strong as a noise pulse would suppress the pulse; in AM a signal had to be one hundred times as strong. Also, FM displayed a capture effect -- that is, if two stations on the same frequency arrived at the receiving antenna with different signal strengths, the system would grab the stronger one rather than pick up both at once. The capture effect, together with the fact that VHF signals cannot be received farther than about fifty to seventy miles from a transmitter, suggested that FM stations in not-too-distant cities could operate on the same channel.

Thus, the advantage of FM resided not simply in its high fidelity, with which AM could compete, but in a combination of effects, the most significant of which was its spectacular ability to suppress atmospheric and internal electronic noise. In notes written in the receiving log at Westhampton Beach on June 9, 1934, Armstrong reported: "1 PM. W2XDJ signed off. All tests performed exactly according to Hoyle. This experiment concludes just twenty years of work on this problem...An era as new and distinct in the radio art as that of regeneration is now upon us. After ten years of eclipse my star is again rising."

In fact, the worst was yet to come. On May 21, 1934, the Supreme Court resolved the long-festering and bitter battle over the invention of the regenerative circuit by deciding in De Forest's favor (the matter was a complex issue of priority in which each side presented a strong case). Though the Institute of Radio Engineers refused Armstrong's offer to return the medal it had given him in 1918 for the regenerative circuit, it could not restore the inventor's loss of dignity.

However serious the wound was, Armstrong would not let it deter him from his work with FM. But in April 1935 RCA asked Armstrong to remove his apparatus from the Empire State Building so that the company could use the space for its experiments with television. Not wanting to postpone the introduction of FM indefinitely, Armstrong then resolved to establish the medium himself, bank-rolling it with his own money and licensing the patents to small companies, just as he had done twenty years before with regeneration.

In preparation he enlarged his laboratory staff, moved into a spacious apartment overlooking the East River, which became both home and office, and secured additional patents on a number of improvements to FM. On July 18, 1939, he began broadcasting from the first FM station, W2XMN, which he had built entirely with his own money in Alpine, New Jersey. That year General Electric began manufacturing -- under Armstrong's license -- the first commercially available FM radios. By the end of the year the five-year-old Federal Communications Commission (FCC) had received 150 applications for permits to establish FM stations.

In 1940 RCA offered Armstrong one million dollars, with no payment of royalties, for his FM patents, but by now the inventor was stubbornly determined to hold onto them and continue licensing. Full commercial FM broadcasting was authorized by the FCC on May 22, 1940, and forty channels were allocated in the forty-two to fifty megahertz range. But then the commission began to express concern about sky-wave interference in the designated FM range -- the possibility that signals reflecting from the ionosphere (a layer of electrified air in the upper atmosphere) would cause interference in receivers. This later became a major issue in battles between Armstrong and RCA.

In 1940, the National Television Systems Committee, which was recommending standards for television, chose to back FM for the television sound signal and AM for the picture. The FCC went along with this when it authorized commercial television service on July 1, 1941. This use of FM was a coup for Armstrong, but the economic benefit for him was slight.

World War II halted FM aural broadcasting early in 1942, and Armstrong devoted himself to research in FM radar for the Signal Corps. By now RCA had an FM station on the air in New York that used a transmitter slightly different from Armstrong's; by 1944 there were forty-seven FM stations in the country and five hundred thousand FM receivers.

At the close of the war a Radio Technical Planning Board (RTPB) representing industry interests was formed to advise the FCC on postwar standards and channel allocations. The board supported the FM frequencies that had been established earlier as well as the use of FM for television sound, but the FCC, citing a study warning of sky-wave interference, recommended moving the FM band to 92 to 106 in the megahertz range.

This proposal; was generally favored by the television industry, which would gain flexibility from the higher channel allocation. But television manufacturers that also made FM radios, including Zenith and General Electric, opposed the move. Also against it were the Radio Technical Planning Board, existing FM broadcasters, and Edwin Armstrong. Nonetheless, the decision was made to move the FM band to 88 to 108 megahertz, where it remains today. The FCC allowed a number of stations to operated on both high and low FM bands during a transitional period until new receivers were generally available. But to the FM industry the "FM shift" seemed more like an FM bust, the major effect of which would be to render all existing FM radios and transmitters obsolete, thus crushing the industry and benefiting companies that had been late to get involved with FM.

Sarnoff and RCA, meanwhile, were focusing mainly on television but continued to carry out their own research with FM. After being rebuffed in its attempt to buy out Armstrong's patents, the company decided to try to get around them. RCA's first commercial FM receiver, in 1946, used a supposedly new circuit to remove noise pulses, or unwanted amplitude-modulation signals. The circuit was very effective, but it could easily be seen as simply an adaptation of the limiter-discriminator component of Armstrong's own FM system. Armstrong made an impressive argument to this effect in an ingenious paper before The Radio Club of America. The inventor already believed RCA would emerge a big financial winner -- and he a big loser -- as a result of the FM band change; now his dismay at the company and its chairman, Sarnoff, increased.

RCA's tight control of its own radio patents provoked resentment among competing companies, and in 1946 Zenith repudiated an RCA license package, ceased to pay royalties, and brought triple damage suits against RCA, GE, and Western Electric, among which there had been interlocking patent- rights agreements. Litigation multiplied swiftly into suit and countersuit, and other manufacturers brought charges of patent infringement and restraint of trade against the big corporations.

So Armstrong was not alone when, on July 22, 1948, he filed suit in federal district court against RCA and other companies, charging them with infringing his five basic FM patents and violating the antitrust laws. The case was to be a test of endurance, a Dickensian legal battle that a single man -- even an Armstrong -- could not hope to win. Though represented by one of the finest Wall Street law firms, he found the opposition prepared to fight. "They will stall this along until I am dead or broke," he said. Stall they did. Legal fees mounted steadily while at the same time income from patent royalties dwindled. The financial and emotional strain on Armstrong grew until it became too much.

By 1953 Armstrong was caught in a tragic drama from which he could not escape. His health deteriorated; his once-robust frame now appeared gaunt, and his face haggard, and the twitch in his neck and shoulder became more pronounced. The pressure proved too much for his wife; at Thanksgiving she left their apartment in New York to live with her sister in Connecticut.

Late in January 1954 Armstrong confessed to his lawyer that he had "made a mess" of his personal life and said that he was ready to settle a twenty-one-patent infringement suit that had just been instituted by him. But he could not bear defeat, and the thought of retiring a beaten man was abhorrent. On the night of January 31, Armstrong -- then sixty-three years old -- penciled a two-page note to his wife, Marion, concluding, "God keep you and Lord have mercy on my soul." Fully dressed in his hat and scarf and overcoat and gloves, he went to the window of his apartment and plunged ten stories to his death.

His widow pressed on, continuing the litigation. One by one, favorable agreements and court decisions began to appear. Late in 1954 RCA agreed to a $1,040,000 settlement; the twenty-one-patent infringement suit was decided in Armstrong's favor in September 1959. The legal proceedings did not come to an end until October 1967, when the Supreme Court refused to review a lower court judgment against Motorola. Eighteen years after he had brought suit and thirteen years after his suicide, Edwin Howard Armstrong had won.

Armstrong's inventions and ideas have also triumphed. Today virtually every radio, television, and radar system employs the superheterodyne circuit. Frequency modulation has become the standard of high-fidelity broadcasting all over the world, thanks in part to subsequent developments in the high-fidelity industry and innovative regulatory procedures. Having declined in number between 1950 and 1958, FM stations in the United States began to multiply after the introduction of stereo on records. In 1961 the FCC authorized the modern stereo-FM system and extended an earlier authorization permitting FM stations to sell background music service to banks, stores, and supermarkets. Finally, the FCC ruled in 1965 that FM stations broadcasting to audiences of more than one hundred thousand had to offer original programming at least half the time, rather than simply duplicate AM schedules.

These developments led to a dramatic increase in the number of FM stations, from 990 in 1961 to the current total of 4,965. The FM industry has been given an additional boost by the proliferation of receivers in automobiles. And improvements in solid-state engineering and microelectronics have lent a crowning touch to the fulfillment of Armstrong's dream of realism in the transmission of sound. FM has reached a healthy adulthood, but only after a birth and early life whose turbulence its inventor could not survive.

Carl Dreher

E. H. Armstrong: the Hero as Inventor

The radio in every home reflects the genius of an American little known outside his profession, who expended himself in titanic battles over his legal and financial rights.

THE death of E. H. Armstrong in January 1954 ended the outstanding technological career of our time—one that brought into being devices so intricate that only a small group of specialists can understand them, yet so simplified in practice that they function in nearly every American home. It was a life replete with all the things ordinary human beings long for—and also a life from which most of us would recoil if we were given even a brief preview of what it entailed. *Fortune* said in 1948 that Armstrong could qualify as "the greatest American inventor since Edison and the most important of all radio inventors, including Marconi." Yet perhaps five Americans in a hundred know who Edwin Howard Armstrong was.

As far as a life can be, Armstrong's was planned —and it was he who did the planning. When he was fifteen he informed his parents that he intended to be an inventor. In the classical tradition he did his first work in a garret, though a very comfortable garret in the spacious Armstrong home in Yonkers, overlooking the Hudson. (His father was the American representative of the Oxford University Press.) By the time he was a junior at college he actually *was* an inventor and an extremely important one, though it took time for the fact to be recognized.

What he had invented was the regenerative circuit, known also as the feedback circuit, the oscillating audion, and the ultra-audion—the multiplicity of names reflects its importance—a milestone in technological history and the prize in patent litigation which lasted nineteen years, cost millions in lawyers' fees and lost time, and scarred Armstrong to the end of his life.

Apparently Armstrong's father started him on his career when he returned from a European business trip with a copy of *The Boy's Book of Invention.* Faraday and Nikola Tesla became young Howard's idols. But he began too at this early date to show some of the pugnacity he exhibited in later years when his inventions were at stake. If anyone disturbed his equipment he was furious. Sometimes he would stay in the garret, which was also his bedroom, for two or three days at a time.

When he was eighteen Howard Armstrong went to Columbia University for his electrical engineering degree. It is recorded that he drove a motorcycle between Yonkers and Morningside Heights at alarming speeds, and this was not the first time he had shown daredevil tendencies. He would climb trees, the cliffs of the Palisades on the New Jersey side of the Hudson, and—what was especially nerve-wracking to the neighbors—a high radio mast which he had erected in the back yard of the Yonkers home. There was something more to this than youthful exuberance, for he kept on doing it as he grew up. He liked to take physical risks—all kinds of risks—and if he felt fear it was to a lesser extent than most men.

BOY WONDER

IN 1909 the electrical engineering course at Columbia was only four years, but the teachers were top men like Arendt, Mason, Morecroft, and Michael I. Pupin, the Serbian goatherd who had arrived in the United States in 1874 at the age of fifteen, with a red Turkish fez on his head and five cents in his pocket, and had become professor of electromechanics and a redoubtable inventor. He remained picturesque. "The rotor of a synchronous motor," he would say in his lectures, "is lousy with harmonics." In later years Pupin, swelling with pride, would always refer to Armstrong as "my former pupil."

Except in radio, however, Armstrong was far from brilliant. Morecroft, after Armstrong became prominent, recalled that he had little interest in the characteristics of alternating current machinery and did "rather poorly" in many of his courses. Moreover, he was a nuisance; he spent most of his time in the laboratory setting up intricate radio circuits. At one point he was so much under foot that Professor Arendt told Professor Mason to "get Armstrong and his stuff out of the laboratory."

He received his degree in 1913. By that time he had impressed the department sufficiently with his zeal in research to be kept on as an assistant at $50 a month, correcting papers and doing other routine work. This was the only regular job Armstrong ever had and he did not have it long. He was to come back to Columbia eventually, as professor of electrical engineering, in which capacity he received no salary and did little teaching. For the moment, however, Morecroft felt Armstrong should work six days a week for his fifty a month, and finally he was fired. Armstrong went back to Yonkers, put up a 110-foot mast in the back yard, and continued to experiment.

THE feedback invention was the culmination of a series of discoveries by Armstrong's predecessors. Back in 1883 Edison, experimenting with the electric lamp, found that when a metal plate was introduced into the bulb a current would flow between the plate and the glowing filament, always in one direction. Edison had other worries and did nothing with the discovery; it came twenty years too early. In 1904 there was a need for a detector of wireless waves and a British electrical engineer, John Ambrose Fleming, made a two-element vacuum tube employing the Edison effect.

In 1906 Lee de Forest, then thirty-three and the only one of the great pioneers of radio still living today, introduced a third element into the Fleming valve and really started something. This element, a zigzag wire called the grid, controlled the current flowing between the filament and plate and added amplification to the detecting action. De Forest, a Yale Ph.D., may not have had a completely clear picture of what was happening inside his "audion," as he called it, but no one disputes that he first put the grid into the vacuum tube and thereby opened the door to modern radio—and to Armstrong.

In 1912 and 1913 reports were circulating that some lad up at Columbia had a receiver hundreds or thousands of times more sensitive than the conventional de Forest audion, so that he could receive signals at unheard-of distances. Armstrong demonstrated the device, which he concealed in a black box, to a number of engineers and commercial radio people—among them David Sarnoff, the twenty-two-year-old chief radio inspector of the Marconi Wireless Telegraph Company of America. Later Armstrong disclosed his engineering principles in a classical paper delivered before the Institute of Radio Engineers modestly entitled, "Some Recent Developments in the Audion Receiver."

What Armstrong had discovered was the technique of taking a portion of the current from the plate of a vacuum tube and feeding it back to the grid, where it would again go through the process of amplification and again make available a surplus of current to be put through the same process over and over again. If the feedback was increased beyond a critical point, the tube would become a generator of oscillations. Engineers could envision large vacuum tubes which would take the place of the arcs and sparks and rotating machinery currently in use. The regenerating and oscillating audion was one of those protean devices which revolutionize whole industries. Not only had it been created by a man barely old enough to vote, but he had done it with such superb engineering skill and thoroughness that the most resourceful, experienced engineers could add little or nothing.

Fitting the invention into the existing scheme of things, however, was a more complex matter. The way of the innovator is hard, and innovators make it hard for one another. There is no more ruthless competition than that between inventors, and the claims of an independent individualist like Armstrong had to be assessed on the strength of his patent position, which could be decided only by the tedious and unpredictable action of the courts.

Around 1915, Armstrong was a good buy. He was practically penniless. He would have sold all his rights for $10,000 and a research job at an equally modest salary.. It was just as well for Armstrong that there were no takers, for within a few years, by granting licenses under his patents, he was receiving $7,000 to $8,000 a year in royalties. He could have lived very well had it not been for legal expenses. But five years later, he was in debt $40,000 to his lawyers.

SECOND BULL'S-EYE

ARMSTRONG'S closest friends were the founders and early directors of the Radio Club of America, which is not so much a club as an engineering society. In World War I a large proportion of the members were in the armed services. Armstrong was commissioned a captain in the Signal Corps, sent overseas, and given the job of intercepting German front-line radio communications. It was impossible to pick them up intelligibly at the American listening posts with the vacuum tubes and receiving equipment then available. Armstrong solved the problem by devising a new type of receiver, the superheterodyne, so superior in selectivity, sensitivity, and ease of operation that by the late twenties it had superseded all other types of receivers and still holds unchallenged leadership.

The French made Armstrong a Chevalier of the Legion of Honor for the superheterodyne and the AEF promoted him to the grade of major. Characteristically, he came home from the war without giving notice of his arrival, appearing suddenly on the steps of the Yonkers house, his head swathed in bandages, crying, "I'm perfectly all right, perfectly all right."

The bandages were necessitated by a skin infection which soon cleared up but disposed of the remainder of Armstrong's hair, which had started falling while he was still in college. He had little vanity, though his high domed forehead, quizzical gaze, long upper lip, and firm mouth might have been accounted handsome in their way. When *Time*, in later years, referred to him as the "bald, monolithic professor of electrical engineering at Columbia University" the description was as accurate as it was merciless.

When he returned from France the Radio Club threw a big dinner for him. Every prominent radio man who was in New York or could get there was present. The only absentees were a few opponents in litigation. Armstrong had a hard, packed life but it contained some glorious moments and this was one of them.

Within the next two years his financial situation improved. He had licensed twenty concerns under his regenerative patents; he now sold what remained of these patents, together with the superheterodyne, to the Westinghouse Company. His total receipts from this sale came to $435,000, which in the early twenties constituted a substantial estate. Even so, it was only a fraction of the intrinsic value and Armstrong sold very reluctantly. An important consideration was his indebtedness to his lawyers and the continuing cost of litigation; once he had sold, the further defense of the patents devolved on Westinghouse.

MR. SARNOFF'S SECRETARY

As Armstrong was the technical genius of radio's second phase, David Sarnoff was and remains its administrative genius. Inevitably their lives were intertwined. In 1922 Sarnoff, the ex-messenger boy and wireless operator—one of the most expert who ever tapped a key—was, at thirty-one, vice president and general manager of the Radio Corporation of America. Sarnoff and Armstrong were almost exactly of an age; Armstrong was the elder by two months.

Sarnoff's secretary was a tall girl from Merrimac, Massachusetts, named Esther Marion MacInnis. One didn't get to be Mr. Sarnoff's secretary by looks and charm alone: Miss MacInnis was also intelligent. Armstrong was in Sarnoff's office a good deal, discussing patents and the like, and he was no more immune than other young men. His manner of courting her was in the spirit of the Scott Fitzgerald era. Armstrong had returned from a European vacation with a Hispano-Suiza, in which he took her for a ride on the Long Island Motor Parkway, a private toll road financed by W. K. Vanderbilt which in one respect was the precursor of modern turnpikes—it had no grade crossings. The road was forty-five miles long and an able driver would make it in forty-five minutes or less. According to Miss MacInnis at one moment on this ride the speedometer read 100 mph.

Another incident in the courtship reflected Armstrong's continuing impulse to risk his neck. Early in 1923 the Radio Corporation of America was erecting its first broadcasting stations in New York City, on West Forty-second Street, opposite Bryant Park. The building, which bore the name of the Aeolian pianola company, was over twenty stories high, and there were two one-hundred-foot towers on the roof to support the antennas. Each tower was surmounted by a crossarm on which a man could walk; in the middle, about fifteen feet higher, there was a ball of strap iron symbolizing, somewhat feebly, the world. Armstrong liked to come up to the station and climb all the way to the ball of the north tower, but Sarnoff had written him a sharp letter telling him to stop. By way of retort, Armstrong appeared at the formal reception which marked the opening of the station and (while Sarnoff was officiating as impresario in the studios on the sixth floor) went up to the roof, climbed the north tower, and stood on the ball 350 feet above Forty-third Street while a photographer took flashlight pictures from the crossarm. According to some eyewitnesses, Armstrong did a handstand on the ball. He had not had a drop to drink.

Armstrong sent a set of prints to Miss MacInnis and Mr. Sarnoff, and the next time Armstrong came to Aeolian Hall the engineer-in-charge had the painful duty of informing the inventor of the regenerative circuit and the superheterodyne that he was *persona non grata.*

In a few months, however, Sarnoff forgave him. Nobody, except perhaps Dr. de Forest, could stay mad at Armstrong very long. Nobody wanted to and besides, it wasn't safe; with a man who turned the industry upside down at least once a decade, it was well to be on speaking terms.

Miss MacInnis also remained on speaking terms with Armstrong; she married him on December 1, 1923. While the bride-to-be waited in Merrimac, the bridegroom started out from New York in the Hispano-Suiza, paced by his friend George E. Burghard in a DeLage. A few miles out of New York the DeLage broke down. Armstrong and Burghard took the carburetor apart four times. At 2:00 A.M. they were on the outskirts of New Haven and further progress became impossible.

It was a cold, drizzly night. The two eminent technicians in their $15,000 vehicles did not have a tow rope between them. Armstrong drove into New Haven, obtained a rope, and towed Burghard into Hartford, where they arrived at 6:00 A.M. The DeLage had to be towed to the Bosch plant in Springfield for a new magneto. The next day, in Worcester, the battery fell out. Eventually Armstrong and Burghard reached Merrimac, the marriage was solemnized, and the couple fled south in the Hispano-Suiza.

HOW TO INVENT

THE Armstrong story is not merely a story of inventions, but of invention itself. Americans, even more than other peoples, live by invention—"We live by obsolescence," as Sarnoff puts it—yet most of us haven't the faintest idea of how the thing is done.

In Armstrong's case, one factor was humility. He was always ready to learn from others. He would patiently question the most uninspired engineer to elicit what little the man knew; in return, with equal patience, he would give as much of his own understanding as the other could absorb. In technical debate, when he felt credit for what he had done was being taken from him, he could be harsh and even cruel; the way in which he tore de Forest apart at meetings of the Institute of Radio Engineers is still vivid in the memories of those who witnessed it, forty years ago. But that was in the heat of battle and de Forest was equally harsh toward Armstrong; worse, he was patronizing.

Armstrong's second great characteristic was skepticism. He believed with Professor Arendt that "it isn't all in the books." He never tired of quoting—or quoting his version of—the Josh Billings saying, "It is better not to know so much than to know so many things that ain't so." When he started on a project he went over everything that had been done before to make sure it *was* so. Educated in mathematics, Armstrong distrusted mathematical formulations; he had seen how often, through erroneous assumptions, they made things seem impossible which were actually possible. He invented by observation, instrumentation, hunches, intuition, and reasoning. And he passed over nothing. "Listen, look, and measure" is one colleague's summing up of his technique.

And then, he *thought.* He thought long and hard. Most of us, most of the time, do not think in this way; we live in a fog of self-induced reverie. Armstrong could not have been entirely devoid of this aimless, restful activity, but his mental processes were abnormally purposive. Watching him with a radio circuit spread out on a laboratory table, or just talking with him, you felt the intensity, the preoccupation, the dogged resolution, the overevaluation—for who can do good work unless he is convinced it is more important than it actually is?

Not all of Armstrong's inventions were successful. One was a total failure and another, the super-regenerative circuit (1922), did not bear out the high hopes of its inception. Its selectivity was poor, and the superheterodyne drove it out; the most important effect of super-regeneration was to make Armstrong rich. When first revealed, its performance was spectacular, its weaknesses less apparent. RCA bought the patent for $200,000 and 60,000 shares of RCA stock, and later Armstrong received another 30,000 shares for helping, among other engineering services, to adapt the superhet for mass production. He thus became, and for years remained, the largest stockholder in the Radio Corporation of America.

THE bitter legal controversies of technology are not occasioned by mere greed or vainglory. Such factors play a part, but there are also honest differences as to who did what. Nobody invents by himself. Every inventor stands on the shoulders of his predecessors, and they stand on the shoulders of earlier investigators, and so on back through history.

Every inventor is also dependent on his contemporaries. An art progresses through the efforts, in each generation, of a few major originators, perhaps some hundreds of second-rate originators, and thousands on thousands of run-of-the-mill engineers and technicians who do the common labor. In the realm of ideas the ratio is about the same. For every good idea, there are a hundred bad ones; for every new idea, a hundred old ones. The mistakes and failures are necessary to clear the ground.

Then, as Pupin said, inventions are always partly luck. There comes a time when an invention becomes possible, and at that stage there are usually more than one pair of hands reaching for it. It is not necessarily the most scholarly or most deserving investigator who grasps it first.

THE PATENT WARS

THE patent system attempts to reconcile the conflicting claims which arise out of all this confusion. In a patent conflict the parties—sometimes there are more than two—may all have ethically valid positions. They all made the invention and they may have made it in substantially the same way and at about the same time. Yet, by reason of some slight priority, or verbal dexterity in the description of what is claimed, or purely legal technicalities, one inventor may be doomed to deprivation while another reaps the reward both in fame and money. It is no wonder that at times the in-fighting gets dirty.

Not one of Armstrong's inventions was entirely his own in the sense that his authorship was never challenged. Eventually he lost the regenerative circuit in a heartbreaking decision in which the engineering profession lined up almost solidly behind him but the Supreme Court ruled that de Forest was the legal inventor. The superheterodyne patent was successfully challenged in the United States by Lucien Levy, a French inventor, although the French gave Armstrong a patent and none to Levy. Frequency modulation Armstrong never claimed as entirely his own; as he said, the idea had been kicking around for years, but nobody did anything with it except to prove, by beautiful mathematical analysis, that it was no good.

Alfred McCormack, a brawny, sapient Wall Street lawyer who became Armstrong's attorney in 1928, remarked that Armstrong's inventions were accepted by acclamation rather than by litigation. The acclamation came to him not because he was the only one who had the ideas nor because he was the only one who could make them work—but because he was one of the precious few who had ideas, made them work, demonstrated with pellucid clarity how they worked, knew what was the next thing to do, and went ahead and did it.

The regenerative litigation began in 1915 with patent "interferences" between Armstrong, Irving Langmuir of the General Electric Company, a German named Meissner, and de Forest. An "interference" is the Patent Office proceeding for determining priority among claimants who have all made the same invention. Armstrong beat out Langmuir by six months, Meissner by two. From 1922 to 1934 de Forest and Armstrong alternated as the legal inventors. The case went up to the Supreme Court not once, but twice. The animosities it aroused bordered at times on physical violence, and of verbal violence there was no end.

De Forest tells in his autobiography how Pupin, whom he had regarded as a "kindly friend," burst into a hall at the Bureau of Standards in Washington where de Forest was giving a demonstration of the oscillating tube, bellowing, "What right have you to have that there? That thing is not yours! That belongs to Armstrong!" And when de Forest read a paper on the audion and its evolution at the Franklin Institute in Philadelphia in 1920, Armstrong himself was ordered by the chairman to sit down when he declared that he himself was the inventor of the feedback circuit, and that all de Forest had invented was the audion.

In 1928 the Supreme Court, without reviewing the evidence, decided for de Forest on points of law. Armstrong was severely shaken. After a few days he got in touch with an engineer-friend and asked him to review the voluminous printed record and tell him who was the inventor—he or de Forest. A week later his friend informed Armstrong, over the telephone, that he was indeed the inventor from a technological standpoint, but that it might prove impossible ever to sustain his claim in a court of law. He then urged Armstrong to try to forget the experience, bitter as it was.

"You still have the mind with which you invented the damn thing," he said. "If anything, it's better than it was. You can make other inventions just as important." There was a pause, then Armstrong's voice came over the line in a tone of quiet despair. "There'll never be another oscillating audion," he said.

Others gave Armstrong the same advice. "We all know you invented the regenerative circuit," Burghard told him. "All the engineers know it. What do you care what the courts say?" But

Armstrong insisted on re-opening the case. In the meantime the Radio Corporation had created its patent pool and possessed rights under both the Armstrong and de Forest patents. RCA had no further interest in defending Armstrong —rather the contrary—and withdrew its support. Armstrong spent about $200,000 of his own money carrying the case up to the Supreme Court once more.

This time the court reviewed the evidence but made deductions from it which dumfounded radio engineers. Pupin and other savants protested in the newspapers and technical journals, pointing out the gross errors in the opinion written by Justice Cardozo. Nevertheless the decision, although somewhat altered in its final form, stood in favor of de Forest. Armstrong returned to the Institute of Radio Engineers its Medal of Honor, which had been awarded to him in 1917 for the invention.

But the directors voted unanimously to reaward the medal to Armstrong, and in 1941 the Franklin Institute awarded its medal to Armstrong for his inventions, including the regenerative circuit. In 1942 the American Institute of Electrical Engineers awarded the Edison Medal to Armstrong for the invention of the superheterodyne, the FM system, and the regenerative circuit. De Forest was awarded the Edison Medal in 1946 for the invention of the audion.

Schiller, being asked by some fool which was the greater poet, he or Goethe, replied complacently, "You can thank God for both of us." American technology and industry, and indeed the whole world, can thank God for both Armstrong and de Forest, but in the eyes of engineers Armstrong invented the oscillating audion. And Armstrong was right: there never was another invention of such far-reaching economic and industrial importance, and of such sheer technological beauty, in his lifetime. There was to be FM, but it was not the same.

LIFE WITH HOWARD

IN 1948 Mrs. Armstrong confided to a reporter that while it had been wonderful to live all those years with a genius—she did not use the term but Howard *was* a genius—it had not always been easy. He worked at all hours. Sometimes he would go to bed early, sleep for a while, then get up and work. Some one who liked and admired him complained that he could talk of nothing but radio. Professor Alan Hazeltine, another prominent radio inventor and an admirer of Armstrong's, tells how he waited, starving, until after nine at Armstrong's apartment where he had been invited to dine, because Armstrong, completely absorbed in the matter under discussion, forgot to take his guests in to dinner.

But that was only one side of him. For every story of how Armstrong didn't mix, there is another of how he did—and was a warmhearted and easy success at it. He would have enjoyed more of life if he could have invented a machine for stretching time. He played a good game of tennis until he was past sixty and gave it up only when trouble with his shoulder made it impossible for him to serve overhand. He liked to get off once in a while to a night club, have a drink and a hamburger and watch people. In middle life he loved the circus and musical comedies.

A light drinker, he liked drinking and dilated in spirit with a few ounces of whisky. Mrs. Armstrong says some of their happiest hours came when he would review the day's work with her, over old-fashioneds. They had fewer guests in the later years, but if Howard became something of a recluse it was only because he attempted to do too much for one human being.

His manner of operating an office must have appalled his wife. Howard had Professor Pupin's old office at Columbia but did not use it much. His principal office was in their twelve-room, five-bath apartment in River House, overlooking the East River. A secretary would come down three or four times a week to take dictation. In another room, cluttered up with radio equipment and packing cases and wires running in every direction, Thomas J. Styles, an old friend of Howard's who had been a banker, took care of accounts, payments, taxes, and the like.

In the library Howard sat on an old lounge chair, surrounded by telephones, a Duncan Phyfe sofa, and three tea tables on which he piled the most important correspondence and documents. Eight more tea tables and some chairs formed a kind of outer orbit. He would pile the day's mail on the floor, open it himself, and go through it. He would never write if he could telephone, and he made no distinction between local and long-distance calls.

He was scrupulously, almost morbidly, honest. It is even harder for a man to be a hero to his lawyer than to his valet, but McCormack speaks of Armstrong's "terrific integrity" and says he never overstated a scientific point, even when accuracy would confuse the courts and possibly result in the loss of the case. He loathed the pseudo-scientific pap which is fed to judges in patent cases and never concocted any of it himself. "He was capable of kidding himself in other matters like the rest of us," says McCormack, "but never in science."

Armstrong might be bullheaded or at times naïve, but it was impossible to imagine him performing a mean-spirited act. His friend C. R. Runyan, Jr., who lived near the Armstrongs in Yonkers and knew him from boyhood, describes him as "the damndest, most generous man you ever saw." On a picnic or camping expedition he was always the one who carried the heaviest box, saw that everyone else was comfortable, and did most of the work.

Under a protective crust of reticence, he was extremely sentimental. He kept the Hispano-Suiza in storage and always intended to recondition it. When the Aeolian Hall towers were torn down he bought the strap iron ball from the wreckers. In 1930 he bought for $100 an old shed at Babylon, Long Island, which had housed the first American Marconi marine station in 1902. He presented the shack to the RCA station at Rocky Point to be set up and preserved.

FM: THE TITANS CLASH

If FM is not exactly a revolution that failed, it is one that has not been as successful as it deserves to be. In FM Armstrong conquered nature, but the obstacles raised by men were too much for him. FM was unlike any of his earlier inventions. It involved not only the creation of a new form of radio communication but an effort to divert a complex industry with a large capital investment into a new channel.

The original motive for developing FM was to eliminate natural static, the bane of radio communication. Every inventive radio engineer had tried to lick it and it had licked them all. Apparently nothing could be done. A distinguished mathematical physicist had said, "Static like the poor, will always be with us." But Armstrong was a man who never gave up. The elimination of static was to be his monument.

Modulation is variation in some form that makes possible the transmission of information. In radio, the orthodox method of modulation was to vary the power or amplitude while keeping the frequency constant—AM, amplitude modulation. There was no way of shutting out static with this technique, for static is itself a form of amplitude modulation, present on every frequency. Armstrong's solution was to turn the technique upside down; he kept the power constant and varied the frequency—FM, frequency modulation. The type of electro-magnetic wave thus produced is not found in nature. As Armstrong worked it out, it largely eliminated man-made as well as natural (lightning) static, thus giving radio a silent background: you could actually hear the proverbial pin drop. But it made many existing transmitters and receivers obsolescent.

While, as Sarnoff said, we live by obsolescence, it is the task of the financial administrators to balance obsolescence—which involves loss of capital—against the gains from new devices which can reasonably be expected to replace the capital destroyed. Thus the seeds of conflict are sown between the independent engineer and the corporate administrator—in terms of the outstanding personalities in this case: Armstrong versus Sarnoff.

The Sarnoff-Armstrong alliance was one of the most productive in the history of radio. That they were able to work together for over twenty years is a tribute to the good sense and adaptability of both. They were not only collaborators but friends. After Sarnoff was married in 1917 Armstrong came to the Sarnoffs' house in Mount Vernon so regularly, in the morning before going to work, that the Sarnoff children called him "the coffee man," because Armstrong, declining breakfast, would always say, "All I want is a cup of coffee." Even after the real break had begun, in 1935, Armstrong appeared at the annual meeting of RCA and, when Sarnoff was under the usual fire of dissatisfied stockholders, rose impulsively to his defense.

"I didn't come here to make a speech," said Armstrong. "I didn't come here to get into a row. I have been a stockholder since 1915, since the days of the old Marconi Company. I have seen the inside of radio from the beginning to the end. I want to say that the man who pulled this Company through during the difficult times of the General Electric, Westinghouse, RCA mixup with the government was its President, Mr. David Sarnoff. [Applause] I think you would have been wiped out if it hadn't been for him. I know what I am talking about. I tell you, I wouldn't have his job for $500,000 a year. I don't agree with everything, for I have a row on with him now. I am going to fight it through to the last ditch. I just wanted to tell you what you owe to Mr. Sarnoff."

Sarnoff wrote Armstrong the next day: "Doubtless I have made many mistakes in my life but I am glad to say they have not been in the quality of the friends I selected for reposing my faith." While he still pays tribute to Armstrong, however, Sarnoff says that he grew difficult to deal with. "And you know," he adds, "he liked to fight." This is a half truth, and it is also half true of Sarnoff. Neither went out of his way to fight; men of their caliber have too much regard for efficiency to engage in useless brawls. But neither are they backward in asserting their rights. Once they are in combat, such men fight with zest.

THE basic patent on Armstrong's system of frequency modulation was granted in 1933. The system was further developed and the IRE paper, which traditionally follows the culmination of a major radio research project, was delivered in New York City on November 6, 1935. Up to that time the system had required nearly ten years of experimentation and, according to one estimate, some 50,000 measurements. Armstrong worked on it like a man possessed, seven days a week, holidays included; some years he took only Christmas off.

Late in 1933 Armstrong demonstrated the equipment for Sarnoff and was invited to move it to the Empire State Tower, where it was field-tested for evaluation by RCA and NBC engineers from June 1934 on. The Armstrong and RCA groups did not see eye to eye and in October 1935 RCA informed Armstrong that it needed the Empire State space for its television research project, which had been carried on concurrently. In no pleasant mood, Armstrong moved out his gear, sold a hefty block of RCA stock, and in January 1936 applied to the Federal Communications Commission for a construction permit for an experimental station of his own, to be located on the Palisades at Alpine, opposite his old home in Yonkers. The FCC, after some boggling, granted him the permit; by the summer of 1938 he had a four-hundred-foot tower of his own to climb.

When Armstrong got into a real hassle you had to be for or against him; the middle ground quickly became untenable. The industry was split wide open. General Electric, Westinghouse, Zenith, and Stromberg-Carlson lined up with Armstrong and became his licensees. RCA, Philco, Crosley, Emerson, and other large producers manufactured FM receivers without benefit of Armstrong licenses. Armstrong and his partisans contended that these receivers were strictly *ersatz*. The non-licensees retorted that a large part of the improvement in quality was just a matter of high-fidelity reproduction which could be achieved just as well on AM as on FM. The engineering controversies were loud, involved, and bitter.

Amid the sound and the fury, this much was clear: Armstrong had rescued FM from oblivion and he was responsible, singlehandedly, for inducing—some would say forcing—the industry to recognize its advantages. He could and did reproduce sound with a fidelity and freedom from disturbance previously unknown. The strength of his patent position was something else again: it was possible that the systems not licensed under his patents were legally in the clear. The only claims he had were for the improvement he had actually effected, to the extent that this proved to be profitable—and, in the last analysis, to such amounts as he could compel the industry to shell out if the matter were carried to the courts.

In 1940 Sarnoff held out the hand of compromise. He offered a million dollars for a license under the Armstrong FM patents. The license was to be non-royalty paying: a million dollars in a lump sum, and that was that. And indeed it was. Late in 1954, after Armstrong's death, the suit was settled for "approximately $1,000,000."

Sarnoff, it has been said, likes to collect royalties, not to pay them. Naturally. He was largely responsible for the creation of the RCA patent pool which, however onerous it may have been to some, brought order out of chaos and enabled radio to go about its business instead of engaging in endless, destructive litigation. But Armstrong refused the offer. He already had royalty-paying licensees; and he was determined to keep control, this time, in his own hands.

THIS was a new Armstrong. A lifelong Republican, a revolutionist only in technology, in politics he was one of the most conservative of men. But in this instance Armstrong was bucking the economic and political system which places the interest of the financier before that of the inventor. Armstrong was trying to act like one of those eighteenth- or nineteenth-century industrialist-inventors who, before big business was dreamed of, started their own industries in an atmosphere of total freedom—freedom from either governmental interference or the network of existing financial and corporate interests.

First Armstrong had to hack his way through the electronic jungle. This he did with his old-time brilliance; only a man who felt and sensed and lived circuits could have brought FM into the realm of practicality at all. Then he came up against the thick wall of AM plant and vested interests—which includes, of course, not only property interests but habit, inertia, and all kinds of psychological factors resisting change. He was making some headway against that when the government forbade the manufacture of TV and FM broadcast equipment during the war period.

TV was not yet commercialized, but FM was, and the four-year standstill hurt. Immediately after the war the FCC (on technical advice which Armstrong called "legerdemain" and "engineering skulduggery") uprooted FM from the 40-52 megacycle band and shifted it to 88-108 megacycles, just above the low TV band. With 500,000 FM receivers already in use, the forced move was damaging. Then TV reached the commercial stage and rocked FM back on its heels.

Armstrong spent more than a million of his own money on the construction and operation of the Alpine station and for twenty years most of his own time went into FM. He had envisioned thousands of FM transmitters on somewhat the same basis as local newspapers, so that every community, small as well as large, could formulate and express its views on the radio instead of relying on the nation-wide networks for entertainment and indoctrination. He did not submit gracefully to the relegation of FM to what he called "an auxiliary and uncompensated service" which merely duplicated the AM programs of the chains.

In July 1948 he brought suit against RCA and NBC in the United States District Court in Wilmington, Delaware, asserting in effect that the defendant companies had conspired to discourage FM, had attempted to persuade the FCC to allocate to it an inadequate number of usable radio frequencies, and had illegally obstructed an application of Armstrong's in the Patent Office. In 1953 and January 1954 he filed additional suits against numerous manufacturers of television and radio receivers.

TWILIGHT

IN 1950 Armstrong was sixty years old. Measured by deeds, he had lived much longer. He did, in fact, look ten years older than he was.

Invention, and scientific investigation in general, is as tough a way of life as can well be imagined. Mental and emotional breakdown is one of its occupational hazards. Lawrence S. Kubie, the psychiatrist, writing in the *American Scientist* for January 1954, reminds young scientists that for every successful piece of research there are hundreds which prove only that something is *not* so. "A scientist may dig with skill, courage, energy, and intelligence just a few feet from a rich vein . . . but always unsuccessfully." Or he may be brilliantly successful, as Armstrong was, and still the fate of which Kubie warns may overtake him.

By the summer of 1953, the suits against RCA and NBC had dragged on for five years. The pretrial testimony ran into volumes. Armstrong was spending most of his time on this litigation. During the war years and after, he had been engaged in classified radar work, and toward the end, an apparatus used to pick up impulses reflected from the moon was built under his direction.[5] He was dangerously overtaxed.

Mrs. Armstrong tried to persuade him to taper off. Beyond a certain point devotion to a cause, however admirable, enters the realm of pathology. Mrs. Armstrong felt that Howard had reached that point. Howard, however, was not convinced.

On Sunday morning, January 31, 1954, forty-one years to the day from the legal date of invention of the regenerative circuit, Armstrong telephoned Burghard at about nine o'clock. Burghard's wife had been ill and Armstrong called to inquire about her condition. Burghard was leaving the house and the conversation was brief. It made no particular impression on Burghard; Armstrong sounded perfectly normal. During the day there were three servants at the Armstrong apartment; they left shortly after preparing his lunch. Mrs. Armstrong was in Connecticut. After about one o'clock he was alone.

Sometime during the evening or night of January 31, Armstrong wrote a love letter to his wife, in pencil on two sheets of yellow paper. Then he put on his hat, overcoat, and gloves and jumped out of the thirteenth-story window. He fell to the third-floor terrace. No one heard him. The man who had done more than any other to increase the clamor of the world departed from it without a sound.

What words, what prayers, what music could have availed him more? Perhaps if there were a special liturgy for the inventor, it could say that he creates the future out of the ideas left by the dead and the dying, including himself. Then, except by specialists, his name is forgotten. Armstrong's is the common fate; even now, only engineers and his friends remember him. But the forces of the past and the future worked in him, and if one measure of a life is this capacity to bridge time, the span of his life was high and long.

Armstrong lay dead on the terrace. The sun rose a few minutes after seven. At ten o'clock they found him.

REMINISCENCES

by **Arch C. Doty, Jr.**, K8CFU, **(LF)**

Growing up in Yonkers, New York in the mid-1930's was fun and exciting. My life was enriched as my father had either gone to school with, or knew, a number of interesting people. They included, for example, Joseph Stillwell who, as "General Vinegar Joe," led the Allied troops in Burma and China during World War II; Professor Bakeland who invented bakelite; and Carman Runyon who later was Chairman of REL. There also was a man who followed Dad in high school and, later, at Columbia University: Edwin Howard Armstrong.

My association with Armstrong was primarily because of his close relationship with Carman Runyon, W2AG, whose son, Randy (C.R. Runyon III) was a contemporary of mine, and a friend. As a result of our friendship, I was often at the Runyon's home on North Broadway in Yonkers.

It was at Runyon's home that Armstrong and Runyon built the first FM transmitter which was used for the first public demonstrations of frequency modulation broadcasting before the Institute of Radio Engineers on November 6, 1935. The same transmitter (which often was modified) was used for many public and private demonstrations that followed, both before and after Armstrong built his tower and facilities at Alpine, New Jersey.

To provide room for this transmitter, the Runyons emptied a spare bedroom on the second floor of their home. A shelf approximately 12 inches wide was built completely around the room, and the various "breadboard" components of the transmitter were placed on this shelf. The transmitter started with the audio input near the door and the succeeding segments: oscillator, IF's, discriminator and RF sections taking up what must have been 30 lineal feet of shelf space. The final amplifier was at the end of the row near a window that allowed access to the antenna. The room was all the more impressive (and I can see it distinctly now, 55 years later) as it contained no furniture -- this provided ample space for visitors who were allowed in the room with the admonition: "Keep your hands in your pockets, boys!"

Evenings at the Runyon's were particularly interesting if "The Major" was visiting, as often happened. For example, on one memorable evening, Runyon and Armstrong had obtained a prototype of Hallicrafter's Dual Diversity receiver (SX-88?). The whole evening was spent in tuning the Ham bands with two antennas connected to the dual front ends of the receiver, and in watching the great variations in signal strengths provided by each. Even smaller boys -- including the future K8CFU -- were allowed a chance to play with the "New Toy."

While he was at Runyon's, Armstrong was relaxed, extremely interesting to listen to, and sincerely cordial to the Runyon family and their friends.

I left Yonkers in 1940 but took with me a fascination for Amateur radio that had been born in the Runyon's study in 1935 and that has stayed with me for the rest of my life.

In 1959, I wrote to Carman Runyon to thank him for his kindness to the Yonkers teen-ager in the 1930's, and to report that my career in electronics had stemmed from that association. In his reply of July 14, 1959, he commented: "It's always nice to learn that a look at one's Amateur station has been remembered for so long a time. I am glad indeed that you have gotten into this fascinating art."

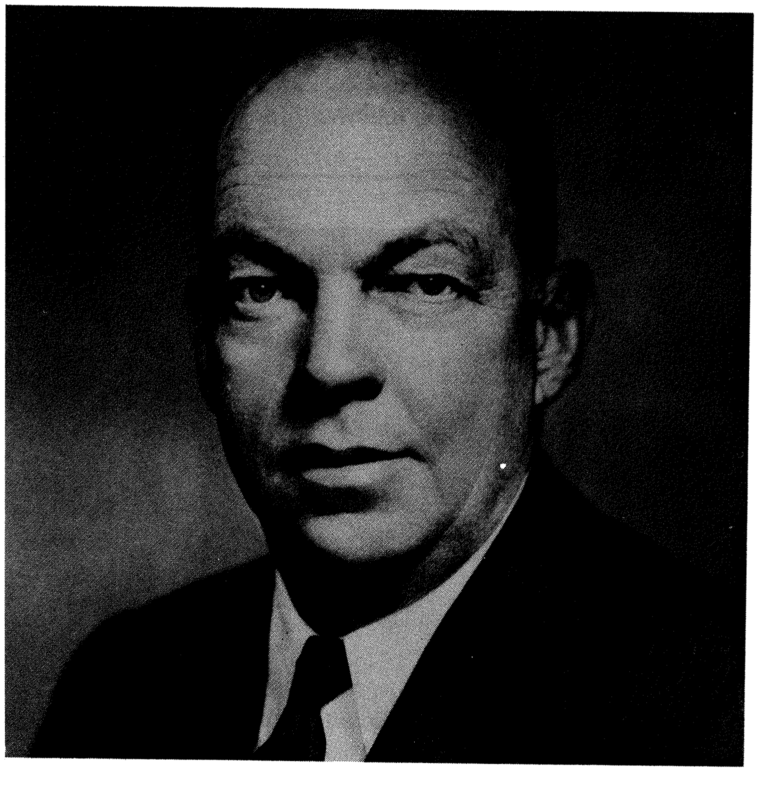
So am I !

E. H. Armstrong

Thomas J. Styles

The booming voice of Professor Pupin emanating from Room 209 Philosophy Hall, in which he lectured, is well remembered by this writer, when no distracting noise in the immediate neighborhood of that room was tolerated. This same room, long since soundproofed and altered by Armstrong at his personal expense, is now used by this writer and the Armstrong Memorial Research Foundation. In this room, Armstrong studied under Pupin, and was usually the first to correctly answer when Pupin, lecturing on electrical theory and great discoveries, would suddenly wheel around and ask "Who made it?" During his lectures, the Professor often used the expression "lousy with harmonics" to the amusement of his students.

During Armstrong's student days, Professor Pupin, with a $20,000. research grant, acquired a huge Crocker-Wheeler earthgrounded alternator with which he planned to do some continuous wave "wireless" signalling. Before he could get off to a start with it, however, the student Armstrong brought out his regenerative or "feedback" circuit, simpler and lighter in comparison and, when employed as an oscillator, far more effective than the heavy alternator of Pupin.


Prof. E. H. Armstrong

Pupin abandoned use of his alternator. It remained in its place for many years, serving as an object lesson for others. After Armstrong's demise, it was disposed of to a junk dealer, who reduced it to scrap with acetylene torch and sledgehammer blows, under the watchful eye of Professor John Walsh of the Department of Electrical Engineering.

During Armstrong's freshman year at Columbia, the writer met him for the first time at a small gathering of "wireless" amateurs in Yonkers, N. Y., home town of both, and was impressed by his serious mien and knowledge of the then young and primitive art; when coherers, spark gaps, crystal detectors, headphones, home made receivers, variable condensers, spark coils and Morse code were the vogue; when there was little or nothing in the books to guide one. A few Audions, or three-element tubes, gassy and low in vacuum, were obtained by amateurs, Armstrong and the writer among them, who could afford five dollars for them "under the counter," from the glassblowers who supplied them to Dr. Lee DeForest, inventor of the Audion. These tubes had little or no superiority over crystal detectors, and the Armstrong "feedback" circuit was as yet unborn.

The possibility of somehow obtaining greater amplification of the signal from the Audion by some as yet undiscovered means intrigued Armstrong. Other amateurs, meanwhile, resorted to higher powered spark transmitters to extend their range, this writer among them. Armstrong prophesied that more sensitive receivers would be the future means of increasing transmitter range, that too much power was being wasted for too short a range. He was then close to the discovery of regeneration, for in the Fall of 1912, during his senior year at Columbia, up in his attic room at 1032 Warburton Avenue, Yonkers, in which most of his off-campus experiments were conducted, he demonstrated to the writer the phenomenal results obtained from the use of his feedback circuit.

He astonished the writer by tuning in a San Francisco Poulsen arc C.W. station communicating in Morse code with another Poulsen arc station in Honolulu. Then he tuned his feedback receiver to the "compensating wave" of the San Francisco station, thus bringing in the intervals or spaces between each dot and dash, instead of the dots and dashes themselves. This puzzled the writer because of his inability to read anything intelligible from these space impulses until Armstrong explained it and suggested remembering this experience as one which might some day be important. The changes in signal note or frequency, and the hissing sound when the tube went into a state of oscillation, were strikingly impressed upon the writer's mind and proved of importance to him later when called upon to testify as a witness to these peculiarities of the feedback circuit of Armstrong. On January 31, 1913, Armstrong gave another Yonkers attic demonstration of his feedback invention to the writer and two others—William T. Russell and John F. Shaughnessy. This date was later established as the Armstrong date of invention.

Armstrong frequently telephoned the writer at his home and talked for long periods on his pet subject, radio. In one conversation, the day before Columbia's 1913 Commencement, Armstrong expressed his happy anticipation of receiving from President Butler, on the morrow, his E.E. degree. That summer in 1913 he was appointed a laboratory assistant at $600 per year, and the following year was made research assistant of Professor Pupin.

In those days meetings of the Institute of Radio Engineers and of the Radio Club of America (founded in 1909, before the I.R.E.) were held on the Columbia campus, when the writer saw Armstrong frequently. Armstrong read papers before both of these bodies. Following a paper delivered by Armstrong before the I.R.E. in March 1915, on Regeneration, DeForest entered into a correspondence discussion on the paper with the I.R.E. Proceedings editor, challenging Armstrong's priority of invention of the Regenerative, or feedback, Circuit. DeForest had given no explanation theretofore of how his Audion tube functioned, while Armstrong, in a December 12, 1914 article in "Electrical World," had given the first correct explanation of the Audion's action, supported by oscillograms made with the help of Professor Morecroft at Columbia.

The U.S. Patent Office, on October 6, 1914, issued to Armstrong the historic Regenerative Circuit Patent No. 1,113,149. Nevertheless there were to ensue many years of litigation all the way to the U.S. Supreme Court, where DeForest was awarded priority of invention on the basis of some notes of his about a "phenomenon" which the engineering world knew to be identical with an effect known as telephone howl. Despite the Supreme Court's crushing decision, which nullified Armstrong's patent—a decision which was based on law but not on facts as those then experienced in the radio art knew them—several scientific bodies upheld Armstrong as inventor of the Regenerative Circuit, among them the Franklin Institute, which awarded him the Franklin Medal, and the Institute of Radio Engineers, which refused to take back from Armstrong its Medal of Honor previously awarded to him. The American Institute of Electrical Engineers awarded him its Edison Medal; the American Society of Mechanical Engineers its Holley Medal; and the Western Society of Engineers gave him its Washington Award.

In 1917 the country was on the verge of war with Germany. Many Radio Club members, prior to the declaration of war, volunteered for Army and Navy duty, where their radio experience was needed. The writer joined a Naval Aviation Detachment in Florida and made some open cockpit flights to test out a quenched spark transmitter, whose energy was obtained from a wind-driven generator mounted on the leading edge of the plane's wing. With a key strapped to his knee he tapped out Morse code messages to the land base. The pilot was obviously nervous about the whole thing, being fearful of the wireless spark igniting the plane's gasoline. Subsequently the writer received a Navy commission at New York and was assigned to aircraft radio duty.

Armstrong was commissioned a Captain in the U.S. Army Signal Corps, was ordered to Paris, and reported for duty at the U.S. Signal Corps laboratory there. He became deeply engaged in improving radio communications for the American forces, developed the Superheterodyne Circuit, was elevated to the rank of Major, applied for a U.S. patent on the superhet, became a Chevalier of la Légion d'Honneur, and in 1919 returned to the United States. He was welcomed back to Columbia with open arms. Radio development, meanwhile, was being greatly speeded in its transition from code to voice. Broadcasting was not far away.

Armstrong's return from his war service found him already embroiled in the litigation with DeForest previously referred to, a litigation destined to continue for another fifteen years. The writer soon followed him back to civilian life.

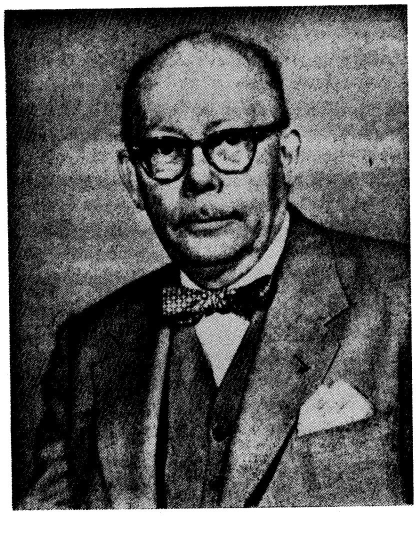
Thomas J. Styles knew Howard Armstrong when both were young radio amateurs. He was Armstrong's confidante at the time of the invention of the regenerative circuit, secretary-treasurer of the Armstrong Research Corporation which held the major's patents, and signed checks aggregating $2,600,000 while acting as Armstrong's financial agent. It was Tom Styles who plotted the characteristic curves from Armstrong's experiments, drew the final versions of the circuit diagrams, and served as witness to the new discoveries.

Mr. Styles began his career as the secretary to a vice president of the Bankers Trust Company in Wall Street. This work was interrupted by World War I, when his experience with wireless was needed by the Navy. With the war over, he returned to the bank and was assigned to the Paris office.

Armstrong, on a European visit, asked Styles to return to the United States as his assistant, and the offer was accepted in 1924. He became associated with the Marcellus Hartley Research Laboratory, of which Armstrong was director.

After Professor Armstrong's death in 1954, the Armstrong Memorial Research Foundation was established with Tom Styles as Secretary. One of the original directors and currently serving is Dean John R. Dunning.

Both Mr. and Mrs. Styles hold Columbia degrees. He is a past president of the Queens County Grand Jurors' Association and was a candidate for Congress in 1940.



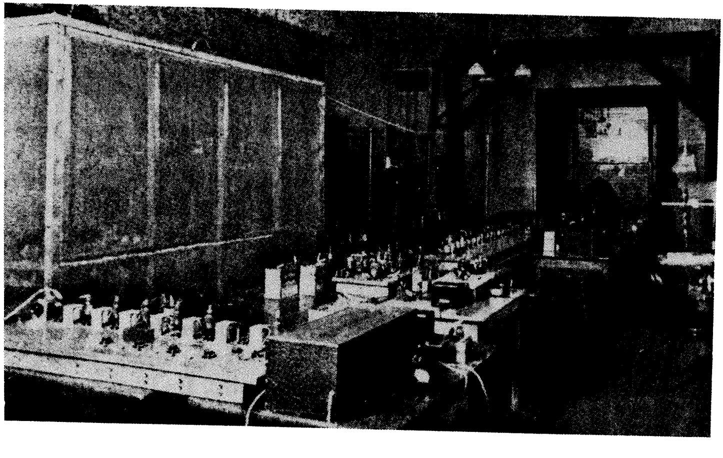
The Radio Club of America, whose meetings had been suspended for the war's duration by Armstrong, its President, resumed its war-interrupted activities. The Club tendered Armstrong a "welcome home" banquet in New York in the spring of 1919, at which Dr. Pupin was an honored guest. Pupin pointed with some pride to his former pupil, Armstrong, the amateur turned inventor who had served his country with distinction in time of war and had made the Superheterodyne invention under the stress of that war. He advised other amateurs and experimenters to "monkey with your sets." Many of those present were, or later became, prominent in the radio art and industry, men such as Sarnoff, Hazeltine, Goldsmith, Hogan and others.

In early 1920 this writer was assigned to the Paris Office of the Bankers Trust Company, remaining there for nearly four years. He was not to see Major Armstrong again until October, 1922, when the Major decided to take a vacation and renew some old acquaintances in Paris.

On December 11, 1921 amateur radio history was made when the first successful spanning of the Atlantic on short waves (200 meters) was accomplished by Armstrong and a group of Radio Club members. They built and equipped a 1 K.W. C.W. transmitting station at Greenwich, Connecticut—1BCG were the call letters—whose signals were heard in Scotland by another Radio Club member using a superheterodyne receiver. This astounded the commercial radio people, as the short waves were considered of no value for such a distance. Their engineers took a second look at these low waves, or high frequencies. Professor Pupin made a trip to Greenwich to investigate. The low waves came into their own thereafter and the art learned more about the "skip distance" phenomena due to these short waves bouncing back to earth from the upper atmosphere. A monument in Greenwich marks the site of the transmitter which accomplished this feat.[1] This writer was in France at the time of the above tests. Two years before, plans were discussed for having him set up receiving equipment in France for such transatlantic tests, but the proper transmitter had not yet been designed. Scotland was later selected for the receiving site.

Upon his arrival in Paris in 1922, Armstrong was in a jubilant mood. He had disposed of his Regenerative and Superheterodyne patents to Westinghouse around 1920 for a reported $350,000. Prior to his arrival in Paris he sold his Super-Regenerative patent to the same company for $200,000. in cash, plus 60,000 shares of stock of the Radio Corporation. Moreover, U.S. Circuit Court Judge Mayer, at New York in May 1922, only a few months before Armstrong's trip to France, had found in his favor in his feedback litigation with DeForest. (This decision was later appealed all the way to the U.S. Supreme Court and, to Armstrong's dismay and that of his friends and others who had lived with the art, DeForest won out in the end, as has been related earlier in this article.)

Prof. Armstrong's lab in 1935



During Armstrong's stay in France he was asked to read a paper on his Super-Regenerative Circuit before the Société des Amis de la T.S.F., a society of engineers and others identified with the radio art. The Major asked the writer to translate from French into English a paper which later turned out to be a French translation of Armstrong's previously prepared English version of his paper on Super-Regeneration which he wanted re-translated into English to see if any errors had crept into the text! Apparently he was satisfied.

A dinner preceded the reading of his paper, attended by such notables as General Ferrié of French Army communications and Professor Abraham of the Sorbonne's science faculty. The writer also attended and was frequently pressed into service as interpreter that evening, particularly between Major Armstrong and General Ferrié.

Before returning to the United States, Armstrong expressed his gratitude for testimony given by this writer in the Regenerative Circuit pre-trial proceedings and urged him, if he ever tired of banking, to consider joining him in research and patent work. In August 1924 the writer decided to give it a try and the association with Armstrong was a fait accompli. Professor Pupin and Mr. Cushman warmly greeted this latest member of the laboratory staff. The unpredictable hours with Armstrong at the laboratory, the long nights of research, were a new experience.

Armstrong's name was a byword among thousands of radio's devotees. One night one of them looked through a Laboratory window, discovered Armstrong at work with rolled up shirtsleeves and in deep thought, and, climbing up on the iron-barred window excitedly pointed out the Major to his companions. The shades were quickly drawn, and drawn they were every time he worked in the Laboratory thereafter.

One of the first research projects Armstrong discussed with the writer after his laboratory association with him, was a new plan of attack on the static problem in its application to radio telegraph signals. His method involved establishment of a difference between natural waves and signaling waves by transmitting two waves of closely adjacent frequency and radiating them alternately, and reception via two paths to balance out the static. A paper-tape ink recorder, such as was in use at the time by the Radio Corporation, was used. After some three years of experimenting, code signals recorded on these paper tapes showed quite some improvement over signals buried in static when his method was not used. In 1927 Armstrong read a paper before the I.R.E. on this method. David Sarnoff of the Radio Corporation visited the Laboratory for a demonstration. However, nothing ever came of this invention, although it appeared to have merit.

Shortly after, in early 1928, Armstrong went into high gear with frequency modulation (FM) as a means of by-passing static and noise in radiotelephone (broadcasting) reception and transmission.

It should be said here that Armstrong was performing his research work independently of Columbia, was not yet a faculty member, and unsalaried of course. This rather unorthodox association with Columbia made it difficult to explain to others at times. In general, it was considered an asset to Columbia to have Armstrong doing his work there. He always made it a point in his publications and lectures to bring in the names of Columbia and the Marcellus Hartley Research Laboratory.

In 1934 Armstrong received a nominal appointment as Professor of Electrical Engineering. His old Professor and former mentor, Dr. Michael I. Pupin, had for some time been suffering from a crippling illness which confined him constantly to a wheel chair. One of the barred windows of the Laboratory was fitted with hinges and a padlock, which was opened on Professor Pupin's now infrequent visits so that he could be wheeled through the window space and into his office. On March 12, 1935, the former Serbian herdsboy who had achieved such scientific eminence passed away. Armstrong thereafter headed the Laboratory.

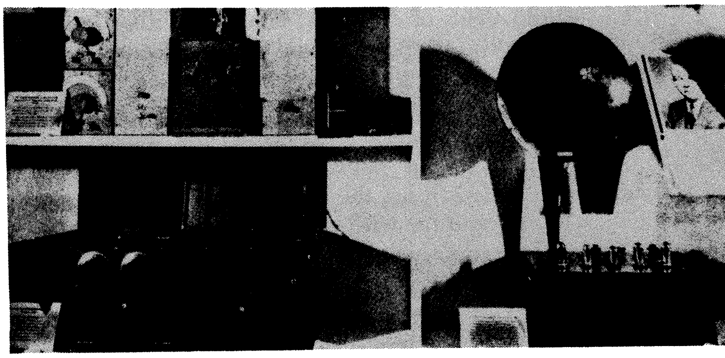
As a Professor, Armstrong, except for some initial attempts, did not teach and would accept no salary from Columbia. He made liberal annual contributions to the University. He maintained his staff and conducted his research at personal expense.

Armstrong was a protégé of Pupin, who saw in him the investigative mind of genius. Like Pupin, Armstrong believed that the text books and the theories of others could oftentimes be wrong.[2]

The development of the Armstrong wide-band frequency modulation method extended from 1928 until its refinement to a point where, in November 1935, it was ready for his paper and demonstration before the Institute of Radio Engineers.[3] The history of this development has been so well covered previously by others that the reader would do well to consult some of the literature on it, especially those mentioned in the footnotes of this article.

To prove to the world that FM worked, the necessity of building his own FM transmitting station became obvious to Armstrong. His Columbia University laboratory staff was increased considerably and an entirely new operating staff for his Alpine FM transmitter was eventually set up. Hundreds of thousands of dollars of his money for construction and operation were poured into the well known station at Alpine, New Jersey with its 400-feet high steel tower piercing the sky—making it stand out as an easily distinguishable landmark on the Hudson River, particularly for aircraft. Armstrong's staff had swelled to eighteen people, and the annual overall operation cost mounted to as high as $200,000., all outgo, no income, from the experimental FM broadcasting part of it.

Prof. Michael I. Pupin, taken in 1927



Equipment used by Prof. Armstrong, now at Smithsonian

A hard uphill fight for public acceptance of the wide-band, noise-free, high fidelity FM method of radio transmission and reception ensued. Others in the art, particularly John R. Carson, had discarded frequency modulation as impractical and without any advantages over the amplitude modulation (AM) method. With the advent of World War II, the production of FM receivers for private consumer use was at a standstill, robbing FM's inventor of any rewards from royalties from that source for the duration. War or no war, the life of a patent is but 17 years and time was fleeting.

The Armstrong FM method ran into many difficulties. It was looked upon with disfavor by the vested interests, so well entrenched in broadcasting with their monopoly of AM stations. FM was considered too revolutionary and a threat to their AM monopoly. Talk-down campaigns were rife. The Federal Communications Commission struck FM a heavy blow by shifting it to a higher band in the frequency spectrum, making thousands of FM receivers obsolete.

Nevertheless, Armstrong's wide-band frequency modulation method was used by the Armed Forces during World War II in some quarter of a billion dollars of FM radio equipment, on which Armstrong waived all royalties for patriotic reasons. After Japan's defeat and the lifting of war restrictions, hundreds of FM broadcast stations went on the air, FM receiver production skyrocketed, and inventor Armstrong collected steadily increasing royalties from manufacturers licensed to use his FM inventions in the production of receivers and transmitters. FM broadcasters paid him a single fee based on the amount of power used.

FM found a ready use for television sound channels. The expensive concentric cables of the telephone people gave way to use of FM for microwave relay stations in transcontinental circuits for the transmission of TV network programs and other telephone uses. Western Union obtained a license to use FM for facsimile messages. FM is built into the early warning system of national defense known as the DEW Line. It is widely used for broadcasting in Great Britain and in West Germany.

Royalties from the FM inventions helped to pay the heavy overhead of Armstrong's Alpine station for a time. There were many infringers. Mrs. Armstrong made a gift of the Alpine station to Columbia University. Its Electronics Research Laboratories now uses it for research purposes.

THE LATE EDWIN H. ARMSTRONG

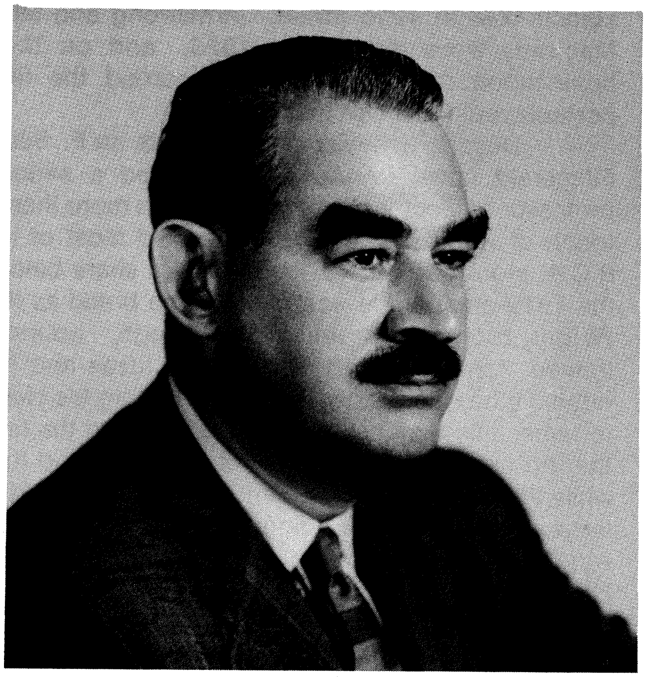
by **Lawrence P. Lessing**

Originally published in *Scientific American*, 190 (April 1954), 64-69.

The tragic death of the principal creator of modern radio occasions this brief review of the trials and tribulations and achievements of an independent inventor in the U. S.

When Edwin Howard Armstrong jumped from a 13th-floor window of River House in New York City on February 1 (1954), there died one of the authentic inventors of our time. He had conceived the three basic circuits upon which rests the whole of modern radio communications. The first is the regenerative feedback circuit (1912) which took wireless telegraphy out of the spark-gap, crystal-detector stage into continuously amplified sound; the second is the superheterodyne (1918), which underlies all modern radio and radar reception; the third is wide-band frequency modulation or FM (1933), a novel system of high-frequency broadcasting which excludes noise and is the core of developments in high-fidelity sound.

Though Armstrong received many professional honors and large financial rewards, he was not the stereotype of a great American inventor. He was born in New York City in 1890, the son of John Armstrong, who was for many years U.S. representative of the Oxford University Press. In this comfortable, bookish household, later removed to a big house in Yonkers, young Armstrong was soon absorbing the stories of Watt, Volta, Hertz, Tesla and Marconi, devouring the works of Michael Faraday, who remained his lifelong idol, and rigging wireless contraptions in the attic like other young "hams" of the day. At Columbia University, to which he commuted from 1909 to 1913 on a red Indian motorcycle, he entered electrical engineering and came under the inspirational teacher Michael Pupin. From his early teens he had shown the urge to go beyond textbooks into the unknown. He made his first great invention while still a junior at Columbia; his second while still in his twenties, serving as an Army Signal Corps Major in France. At the war's end he returned to Columbia to teach, experiment and eventually take over Pupin's chair, a position which, with its precious freedom to investigate, he never relinquished.



Lawrence P. Lessing

Armstrong's early inventions, vital to the lusty new radio industry, brought him almost immediate wealth. In 1912 his father had refused him $150 with which to file a patent application on his feedback circuit, asking him to wait until he was graduated. In 1913, when he filed the patent, he would cheerfully have sold it for $10,000 and a job. None of the big communication companies made an offer. Right after the war, however, the Westinghouse Electric & Manufacturing Company offered him $530,000 over 10 years for both his regenerative and superheterodyne patents, and he sold them. (Later the government forced the radio industry to pool all electronic patents, and the right to license them for radio use was centered in the new Radio Corporation of America.) In 1922 Armstrong sold a lesser invention, the super-regenerative circuit, to R.C.A. for $200,000 and 60,000 shares of R.C.A. stock, which was later raised to 80,000 shares for consulting services, making him the largest individual stockholder in the corporation.

Armstrong, then 32, went to Europe, lived expensively and brought back a Hispano-Suiza to indulge his love for fast cars and to dazzle R.C.A. President David Sarnoff's secretary, Marian MacInnis, whom he was courting. One windy night, to impress her, he impulsively climbed to the top of the 400-foot transmission tower of the new radio station WJZ in 42nd Street. Armstrong and Miss MacInnis were married in 1923, and on their honeymoon to Palm Beach he carried the first portable radio, built for the occasion.

Despite behavior that suggests an F. Scott Fitzgerald novel, Armstrong remained a serious professor of electrical engineering, with more than a touch of worldly shrewdness (he sold most of his R.C.A. stock at a peak price of $114 a share before the 1919 crash.) He was of the same breed as the Wright brothers: practical, thorough, soundly trained, tenacious in defense of his ideas and his rights. If he was successful in establishing his claim to fame, this may have been due partly to the fact that he was never his own best advocate and that while the Wrights' achievements were soon visible in large, shining vehicles riding the skies, Armstrong's were as invisible as the radio waves carrying a song. His major accomplishments were contained within the vacuum tube.

In 1939, when I first met Armstrong, he was at the height of his long battle to establish FM. In 1935 he had demonstrated FM before the Institute of Radio Engineers and in months of successful tests in R.C.A.'s facilities atop the Empire State Building. Getting no action from the industry and finding himself stalled by the Federal Communications Commission on a license to erect an experimental FM station of his own, he threatened to take it to a foreign country. In 1937 he was allowed to build a full-scale FM station, in which he invested $300,000, at Alpine, N.J. In the next two years he gave demonstrations of FM's superior radio quality to all who would listen.

The demonstration I attended started with a briefing in his Columbia laboratory, from whose walls two portraits of Faraday looked sternly down; afterward Armstrong drove us first to Alpine and then far out on Long Island to the house of a friend who had an FM receiver. When the set was turned on, the Alpine program came in out of a blank silence, as if there were no receiver at all. Armstrong telephoned an assistant at Alpine: "Suppose we have a few tricks first, John." A match was struck, a glass of water poured, a gong tapped, and all were reproduced on Long Island with utmost faithfulness. Then a pianist began a Mozart sonata, and there issued from the black box such full, natural tones as had never been heard before. FM broadcasts were repeatedly recorded at this location with the same steady, limpid clarity through thunderstorms and other atmospherics that made ordinary radio an affront to the ear more than half the time.

Short-wave FM was not merely a tonal advance but a different broadcasting system. It made possible many more radio stations and networks than could ever be crowded into the limited long-wave radio bands. The inventor offered the FM patents only for licensing, not for sale. He was determined to administer FM himself in order to control its quality. Regular radio, to his sensitive ear, had had its technical standards steadily lowered by the overcrowding of stations in limited frequencies and by a flood of inferior receivers. Naively, he was shocked by the stony silence and opposition with which most of the industry greeted FM. The industry coldly informed him that the public was not interested in high fidelity, and moreover, with television just on the horizon, that FM had come too late. Armstrong never forgave this rebuff.

Like his model Faraday, whose discoveries founded the electrical industry, Armstrong was an original, non-mathematical thinker in electromagnetic waves. He shied at equations, not because he was ignorant of mathematics but because he preferred to think first in physical terms of particles, currents, frequencies, circuits, then to reduce his observations to mathematics. Too many discoveries had been put off by figures which said they were impossible. His forte was the sharp analysis of unambiguous physical phenomena. He was never so happy as when flying in the face of some accepted theory or confounding an unimaginative engineer. His deepest reverence was for "the laws of nature." Though his discoveries were not basic as Faraday's, they went far beyond narrow invention.

This is well illustrated in his working out of the regenerative circuit. In 1883 Thomas Edison observed a mysterious effect. Experimenting with a plate inserted in an incandescent lamp, he noticed that when he connected the plate to the positive terminal of a battery, a current leaped across the space between the lamp's hot filament and the plate. Edison passed over the phenomena as insignificant. It took until 1904 for an English physicist, Sir John Fleming, to puzzle out the "Edison effect" and put it to use in the Fleming valve -- the first electronic tube. It had two elements: a filament and a plate. Two years later, in the U.S., Lee deForest added a third element -- a metal grid between the filament and plate which could control or modulate the current across the space by small voltage changes on the grid. He thereby created essentially the electronic vacuum tube of today.

Its possibilities for radio were not recognized at the time. Again a tiny effect was observed, which deForest passed over and failed to explain. When the tube was tuned to a certain frequency as a circuit, it emitted a faint, long-drawn whistle. In 1911 young Armstrong found the answer. Like a dozen more eminent investigators he was searching for a means of amplifying wireless signals, which were then too weak for effective transoceanic communication. Testing and analyzing the tube's performance, Armstrong came to the startling discovery that, properly hooked up, it was a powerful amplifier. The whistle deForest had heard had been the tube imperfectly amplifying. When the tube's electrical output was purposefully fed back on the input line to the grid in an endless loop, it multiplied weak incoming signals hundreds of times. When, later, Armstrong allowed it to amplify beyond a certain value, the tube began sending out its own oscillating, high-frequency radio waves. In 1914 Armstrong wrote two historic papers fully delineating the regenerative feedback principle and plotting the first curve -- now an engineering commonplace -- showing how the vacuum tube really worked.

His next inventions, which came in short order, were of the more striking "accidental" sort. He was led to the superheterodyne by a mathematical dispute over a circuit called the heterodyne. He solved the problem by experimental means, and its solution, plus two chance observations on unrelated military problems, suggested a circuit which would overcome feedback limitations and give thousandfold amplification. The next investigation was pure chance. While resetting his regenerative apparatus to prove that a patent lawyer had garbled a law of nature, he suddenly pulled in an amazingly loud signal. This proved after some days of analysis to be super-regeneration, now used in special military and police systems. "Ninety-nine out of 100 experimenters," said his coworker Alan Hazeltine on presenting him with the Edison Medal of the American Institute of Electrical Engineers in 1942, "would have failed either to notice the effect or to find its cause."

FM came at the end of a dogged, 20-year search in which Armstrong had chased many will-o'-the-wisps. Static in radio is essentially the same electrical phenomenon as the radio signal itself: *i.e.*, amplitude-modulated waves of varying power. Hence it is extremely difficult to keep static out of AM radios, even with heavy power and ingenious filters. Searching for a way around this impasse, Armstrong about 1925 found a way to transmit signals by varying not the power but the frequency of the waves. Many experimenters had tried this and pronounced it unworkable for radio use. But all had attempted to employ FM like AM radio, transmitting it on as narrow a band of frequencies as possible for sharp tuning. Armstrong conceived the idea of allowing the frequencies to swing over a wide band. This not only made FM workable but allowed for the full frequency range of the human voice and music. The band width required put FM up into the more spacious, relatively untenanted ultrashort waves where there is less static to deal with.

In essence Armstrong's solution was to employ a type of electromagnetic wave not normally found in nature. Generated by a specially designed transmitter and sent to a special receiver, it forms a closed system into which normal static cannot break. Since the signal's amplitude is held constant, FM can operate on a small fraction of the power of AM radio with a clarity unmatched by the most powerful clear-channel stations. Its range, however, is limited to not much more than the horizon.

Most of Armstrong's work was done in the arena where the patent and research departments of great corporations contend for advantage. He had an early baptism of litigation. In 1914, shortly after Armstrong filed his feedback patents, deForest applied for patents on a similar system called the "Ultraudion" circuit. Armstrong received his patents in 1914, deForest in 1924. For 12 years a violent battle was fought in the courts. The radio industry first backed Armstrong's patents which it owned, then switched to deForest's which it also owned but which had an additional 10 years to run. Armstrong carried the case alone up to the Supreme Court, seeking vindication. The Court, following the technical facts with difficulty, found for deForest. Shaken and emotionally distraught, Armstrong returned to the I.R.E. a citation and medal it had awarded him in 1917. The organization refused to take it back. In 1941 and 1942 two technical juries, after again reviewing the case, awarded Armstrong the Franklin Medal and the A.I.E.E. top medal for his three major inventions.

FM was to give Armstrong an even worse legal headache. In 1940 the Federal Communications Commission awarded to FM radio the frequency band it had previously given to experimental television, moving the latter to a higher frequency. In addition, it ordered all of television's audio circuits to be changed to FM, as they are now. Soon, 40 FM stations and 500,000 sets were operating. The large AM networks added FM facilities.

After World War II (during which FM served in most of the mobile short-range military communications) the F.C.C. dealt FM broadcasting two severe blows. It moved the broadcasting to higher bands, making all transmitters and sets obsolete, and, on an AM network suggestion, it drastically cut the allowable station power in order to limit each station to a "single market" area. This hurt small networks of independent FM stations, which had been relaying programs by air from one station to another. Nevertheless, by 1949 there were more than 600 FM stations on the air, and high-fidelity radio has now become a $300-million-a-year business.

Throughout all this, only a few manufacturers paid Armstrong royalties on his FM patents. Most set-makers used a type of FM (the "ratio detector"), first heard of in 1946, which Armstrong charged was merely a cut-rate, inferior version of his invention. He brought suit. The suit dragged on in pretrial hearings for five years.

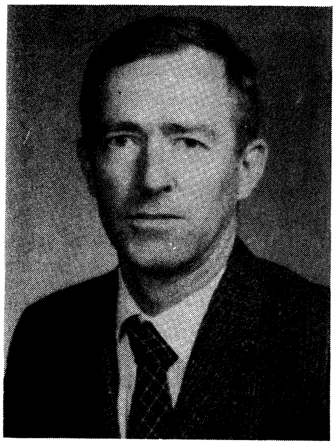
Bitterest of all to Armstrong was the fact that FM showed no signs, as he and others had predicted, of supplanting AM radio. The AM networks merely duplicated their AM programs on FM, developed few if any live programs for FM standards and failed to develop independent advertising revenue from FM outlets. Small, independent FM stations, isolated in single markets, had rough sledding economically and, therefore, artistically, and many went out of business. Armstrong himself anonymously put up some $1,200 a month for high-fidelity toll lines between Washington and Boston to hold the old FM Continental Network together for such programs as the Library of Congress chamber music series. He also kept his old Alpine station going. This station operated for 16 years at a cost of more than $1 million. Finally, after his death, it was shut down.

Armstrong's life was a mixture of great achievement and of nagging adversities which finally killed him. Perhaps he might have been happier if he had followed Faraday's example of renouncing the financial exploitation and rewards of his discoveries. Yet if he had not pressed FM, it might still be only a document in the Patent Office. He, like Marconi, toward the end of a busy life, looked longingly and prophetically at the microwaves, in which he was certain there were discoveries yet to be made, but his trials did not give him time.

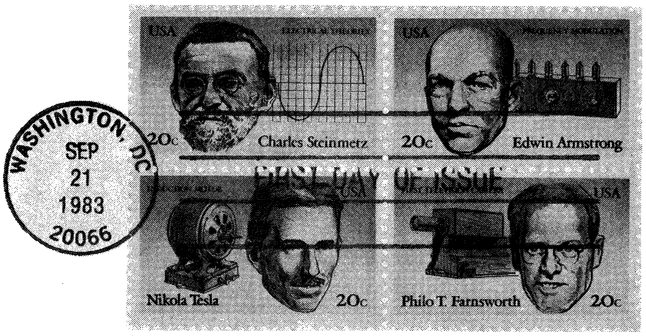
At the end he was weary of the battle. I talked with him late that December. His basic FM patent was running out. His suit showed every sign of outlasting the deForest action. He would not be consoled by the growing popularity of FM and the high-fidelity idea. He had placed great hopes in a new F.C.C., but that was gone. He had a sense of failure such as often creeps in upon the best and most creative minds.

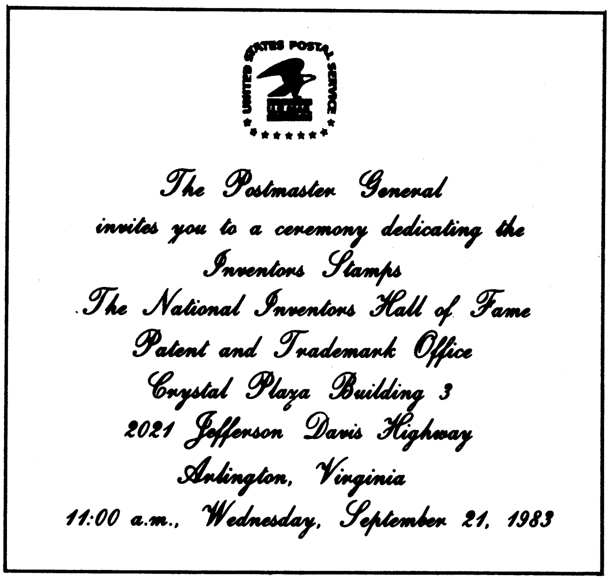
In his big, lonely apartment overlooking the East River Armstrong wrote a last letter to his wife (who had gone off to Connecticut because he refused to retire and relax). His funeral in the Fifth Avenue Presbyterian Church was attended by his Columbia University associates, some of the world's leading electronic engineers and the captains of the radio industry he had founded. "Greatness," said Ralph Waldo Emerson, "is a property for which no man gets credit too soon."

Edwin H. Armstrong — An Independent Inventor In A Corporate Age



by James E. Brittain, Ph.D.
(M 1983)





The Postmaster General
invites you to a ceremony dedicating the
Inventors Stamps
The National Inventors Hall of Fame
Patent and Trademark Office
Crystal Plaza Building 3
2021 Jefferson Davis Highway
Arlington, Virginia
11:00 a.m., Wednesday, September 21, 1983

On September 21, 1983, the U.S. Postal Service commemorated the 100th anniversary of the founding of the IEEE with the issuance of postage stamps honoring American inventors who were electrical engineers. The four so honored were Edwin H. Armstrong, Philo T. Farnsworth, Charles Steinmetz, and Nikola Tesla.

Also in commemoration of the event, The Smithsonian Institution presented a symposium at the National Museum of American History at which papers were presented on E. H. Armstrong and Charles Steimetz.

James E. Brittain, Ph.D., (M 1983), who is Associate Professor of History of Science & Technology at the Georgia Institute of Technology, presented the following paper on Dr. Edwin H. Armstrong.

* * * * *

Edwin Howard Armstrong is widely regarded as America's foremost inventor in the field of radio technology. His four principal inventions were regenerative feedback circuits, the superheterodyne receiver, the superregenerative receiver, and frequency-modulation broadcast systems. He received approximately fifty U.S. patents and he achieved celebrity status especially within the amateur radio fraternity and the Institute of Radio Engineers. As an independent inventor whose patents became pawns in the arena of corporate conflicts, Armstrong devoted much of his time and energy to efforts to establish his priority in a legal sense as well as in the eyes of his peers. The increasing frustrations that he experienced in these efforts caused his final years to unfold like a Shakespearean tragedy.

Armstrong exhibited an unusual style for a 20th century inventor in the high technology of radio electronics. He showed almost a phobic distrust of mathematical analysis and his well-crafted technical papers rarely contained an equation. Instead he relied on circuit diagrams, oscillograms, and the characteristic curves of vacuum tubes in his explanations. He was like an artist except that his medium was the vacuum tube, the inductor, and the capacitor linked in intricate combinations. He was able to grasp intuitively the effect of altering circuit parameters and to track down the cause of unexpected phenomena that baffled less perceptive experimenters. He followed a pattern that he admired in Marconi by undertaking experiments that challenged the dogma of established theory. Armstrong's career that led from his home attic to the top of the Empire State Building with frequent litigious detours well illuminates the changing environment of the inventor during the first half of the 20th century.

ARMSTRONG'S EARLY YEARS AND THE REGENERATIVE FEEDBACK INVENTION

Armstrong was born in New York City on December 18, 1890 at a time when the electrical age was already well underway. Edison's historic Pearl St. power plant had begun operating in 1882. Nikola Tesla's classic paper on the polyphase power system had been presented before the American Institute of Electrical Engineers in 1888, a year also notable for the culmination of the remarkable electromagnetic wave experiments of the German physicist, Heinrich Hertz. The application of the Hertzian waves in wireless communication was destined to become the principal focus of Armstrong's inventive talents. One of the inventors who also is being recognized during this symposium, Charles Proteus Steinmetz, published his proposed law of magnetic hysteresis in a short paper in the **Electrical Engineer** in the issue dated December 17, 1890, the day before Armstrong was born.

The cultural environment in which Armstrong spent his formative years was ideal for a future inventor of radio circuits and systems. His father was an executive with the Oxford University Press and his mother had been a school teacher. New York City was the center of the emerging electrical engineering profession in the United States as the headquarters of the AIEE since its formation in 1884. The Wireless Institute formed in 1909 and its successor, the Institute of Radio Engineers, were centered in N.Y. City. In fact the first meeting of the IRE was held at Columbia University in 1912 when Armstrong was in his junior year at Columbia.

The New York area also was the center of amateur wireless enthusiasts who enjoyed a kind of golden age during the period when Armstrong was attending Yonkers High School and, later, Columbia. Amateur wireless was a cultural phenomenon not unlike that occuring among young computer enthuiasts today. Prior to the first World War, amateur wireless was a populist phenomena fed by "fantasies of friendship, fame and conquest" and dominated by teenage boys who constructed their own apparatus, and eagerly shared information about the latest advances or achievements with others in the fraternity. Their enthusiasm was encouraged by such writers as Victor Appleton who wrote **Tom Swift and His Wireless Message** and Allen Chapman who wrote a series of adventure stories about the "Radio Boys."

Blessed with indulgent parents, Armstrong was permitted to engage in wireless experiments from his home from the age of fourteen. Later he joined The Radio Club of America and remained an active member for the rest of his life. This club had been formed as the Junior Aero Club in 1907 by a New York schoolboy, W.E.D. Stokes, Jr. The club's initial interest was in flying model airplanes but the focus changed to wireless by 1909 when the club became the Junior Wireless Club Limited and finally was called The Radio Club of America in 1911.

In addition to being the home of the IRE and The Radio Club, the New York City area spawned college programs that were exceptionally strong in radio-electronics engineering. Columbia University, where Armstrong enrolled in 1909, served as a virtual incubator for radio engineers and inventors. If offered not only formal engineering courses and access to good laboratory facilities but also enabled motivated students to acquire information about the latest developments through the meetings of the IRE and The Radio Club that were held frequently at the University. Alfred N. Goldsmith, who received his Ph.D. from Columbia in 1911, taught at City College of New York, and was the editor of the **Proceedings of the IRE.** His laboratory was used for radio research sponsored by GE and later by RCA.

Nearby was the Stevens Institute of Technology where Armstrong's friend Alan Hazeltine graduated in 1906 and began teaching the following year. Hazeltine became a successful radio inventor and later founded the Hazeltine Corporation that employed several engineers with an Armstrong connection.

At Columbia, Armstrong came under the influence of the legendary Professor-inventor, Michael I. Pupin, who had sold his loading coil patents to the Bell Telephone Company in 1900 for almost a half-million dollars. Pupin became a role model for Armstrong as well as an effective promoter of the younger inventor. As independent inventors, the two men shared a low regard for the contributions of in-house corporate inventors. The Columbia faculty that included also Henry Mason and J.H. Morecroft encouraged Armstrong to patent his first invention and even referred him to a local patent attorney. Mason loaned him instruments and Morecroft assisted him in oscillogram tests of regenerative amplifiers and oscillators.

Armstrong discovered the regenerative feedback effects while he was still a Columbia undergraduate. He acquired his first audion tubes in 1911, devices that he later described as having been "clouded in the mystery" of the gas ionization theory of de Forest. Armstrong carried out a careful study of the audion with the aid of instruments at the University. While experimenting with tuned-plate and tuned-grid circuits in the Fall of 1912, he observed the phenomenon of regenerative amplification that enhanced greatly the strength of received wireless signals. He also identified self-excited oscillations in the output of an amplifier with feed-back which meant that the vacuum-tube oscillator could serve as a source of high-frequency waves.

He received his B.S. degree in electrical engineering in June 1913 and remained at Columbia to teach a class in wireless for the Navy and to continue his research.

He filed a patent application on the regenerative receiver in October 1913 and it issued almost a year later. Professor Pupin arranged for the regenerative circuits to be demonstrated for representatives of the American Marconi Wireless Company in December 1913, and for engineers of A.T.&.T. early the following year. Neither firm chose to purchase rights to the invention. However the receiver was licensed to the German Telefunken Co. and used by its station at Sayville, Long Island to pick up signals transmitted from Germany.

Armstrong's technical papers on the audion and regenerative circuits made a strong impression on the first generation of radio-electronics engineers. His paper on the "operating features of the audion" in the **Electrical World** of December 1914 employed characteristic volt-ampere curves and oscillograms to show graphically how the tubes functioned. Early in 1915, he presented a paper entitled "Some Recent Developments in the Audion Receiver" at an IRE meeting. In this paper, Armstrong gave a comprehensive explanation of regenerative amplifiers and oscillators, and practical results achieved with receivers at Columbia. This paper precipitated a dispute between Armstrong and Lee de Forest who challenged not only Armstrong's "results and conclusions" but also his priority in the discovery of the feedback oscillator. These first publications by Armstrong later were credited by Alan Hazeltine for having opened his eyes to the engineering possibilities of the vacuum tube and to have exerted a profound influence on his professional career as well as that of many others.

Armstrong remained at Columbia until 1917, as Trowbridge Fellow at the Hartley Research Laboratory. He and Professor Pupin filed five joint patent applications during the period 1915-1917 although none of these were issued prior to the War. In 1916, Armstrong was elected President of The Radio Club of America and, in the same year, he began to receive royalties from the American Marconi Company that finally had decided to acquire a license to use his regenerative receiver.

THE FIRST WORLD WAR AND THE SUPERHETERODYNE RECEIVER

In 1917, Armstrong's talents were diverted to military needs for radio communication and it was during his service in Europe with the U. S. Army Signal Corps that he conceived his second major invention, the superheterodyne receiver. He was given a commission as a Captain and, after a brief period of training, was ordered to Paris, France to establish a Signal Corps laboratory. During a brief stop in England, he learned from Henry J. Round, a Marconi radio engineer, that a critical problem had developed that involved a need to detect very-high-frequency radio signals that the Germans were believed to be using.

Arriving in Paris late in 1917, Armstrong became the leader of a group of talented radio engineers and technicians. Unfortunately the full story has yet to be told of the sociology of the group, their contributions during the war, and their interaction with French and British experts. Among the group's members were Harry W. Houck, Harold M. Lewis, Willis R. Taylor, William A. MacDonald and Jackson H. Pressley. Houck was an amateur radio veteran and an outstanding electronic-circuit craftsman who remained a close associate of Armstrong after the war. Lewis had an engineering degree from Union College and constructed the first working model of the superheterodyne receiver following Armstrong's circuit diagram. After the war, Lewis worked as an engineer-inventor for the Hazeltine Co. Taylor held an engineering degree from Stevens where he studied under Professor Hazeltine, and he later was patent attorney both for Armstrong and Hazeltine. MacDonald had worked for the American Marconi Co. and, after the war, worked for RCA before serving as chief engineer with Hazeltine. Pressley also worked for Hazeltine before becoming chief engineer of the U.S. Radio and Television Co.

The inspiration for the superheterodyne receiver apparently came to Armstrong early in 1918 when he was speculating on whether short-wave radiation from airplane engines might be detected and used to direct the fire of anti-aircraft guns. He was acutely aware of the deficiencies of existing vacuum tubes at higher frequencies, and the superheterodyne principle provided an ingenious solution since it would enable a high-gain tuned amplifier to function at lower frequencies during reception. The first model employed eight tubes, and tests of sensitivity and selectivy were encouraging although the invention was not perfected in time to be used during the war. Armstrong's application for a U.S. patent on the invention was filed in February 1919 and the patent issued in June 1920. Interestingly there is evidence that a German engineer, Walter Schottky, independently conceived the superheterodyne principle early in 1918 during an investigation at the Siemens Labs. Schottky filed for a German patent in June 1918 but he later gave credit to Armstrong and associates for having introduced the new receiveer into practice. A third claimant, Lucien Levy, was a French inventor whom Armstrong met during his service in France and whose patent later was involved in litigation with the Armstrong patent.

Armstrong was awarded the first Medal of Honor of the IRE in 1918 for his feedback discovery, and was promoted to the rank of Major in the Signal Corps early in 1919. He returned to New York in September 1919 to resume his work at Columbia while defending his patents agains litigation. In December 1919, he presented papers on the superheterodyne receiver for both The Radio Club and the IRE.

The environment to which Armstrong the inventor returned after the war had changed in such a way that it provided him with a golden opportunity and quickly made him a millionaire. His position was analogous to that of a small, unaligned nation when two superpowers are seeking a competitive advantage, and his radio inventions suddenly were perceived to have strategic value in corporate radio wars. The major institutional change in the radio environment in the U.S. was the formation of the Radio Corporation of America, in 1919, with a broad mandate to develop international point-to-point radio communication. The Westinghouse Electric Co. had made an entry into the radio-electronics field through the manufacture of military apparatus during the war but saw itself in danger of being excluded from the radio field by RCA and GE, firms with close corporate ties. Westinghouse decided to purchase rights to the Armstrong patents in order to use them for leverage in negotiations with RCA and GE. From this sale, Armstrong realized the sum of $335,000 with a contingency clause that would add another $200,000 if a feedback oscillator patent, that was involved in an interference proceedings, issued. The patents were probably worth the cost to Westinghouse as its principal bargaining chip in a cross-licensing agreement reached with RCA and GE in June 1921.

Armstrong attracted further acclaim in December 1921 when he and six fellow radio enthusiasts successfully carried out an experiment in which a message sent from a 1000 watt transmitter operated at a wave length of 230 meters at a site in Connecticut, was picked up in Scotland by one of the group, Paul F. Godley, on a superheterodyne receiver. The experiment demonstrated that it was not necessary to employ the expensive long-wave 200kw radio alternators of RCA, to communicate across the Atlantic. Armstrong later called the experiment "a turning point in radio history" where "something contrary to what was in the books" had been discovered.

The advent of radio broadcasting and its phenomenal growth during the early 1920s further enhanced Armstrong's reputation and his fortune. The pioneering Westinghouse station KDKA began operation in October 1920 and the number of broadcast stations in the U.S. reached 580 by the end of 1922. A seller's market for household receivers developed and several hundred firms manufactured receivers during the 1920s. Armstrong and Harry Houck helped to develop a commercial RCA version of the superheterodyne known as the "Radiola" that used fewer tubes and simpler controls than earlier versions. Engineers at GE, RCA, and Westinghouse also contributed design improvements before the six-tube sets were introduced to the national market in 1924. The RCA superheterodyne receiver was commonly regarded as the "Rolls-Royce of Radio" during the 1920s and alternative receivers such as Alan Hazeltine's "neutrodyne" were highly regarded competitors until RCA licensed other firms to manufacture the superheterodyne after 1930.

THE SUPERREGENERATIVE RECEIVER

In 1921, while preparing a regenerative circuit as an exhibit for patent litigation, Armstrong invented a sensational new radio receiver that required only two tubes to produce remarkable sensitivity. His lecture on superregeneration presented at a Radio Club meeting at Columbia, in 1922, attracted at overflow crowd who reportedly "simply ate up every word Mr. Armstrong uttered and watched in rapt admiration as he demonstrated his latest development." He attracted what was said to be the largest audience ever to attend an IRE meeting when he spoke on the newest receiver, in June 1922.

In his IRE paper, Armstrong followed his usual pattern of avoiding mathematical analysis. Instead he gave a qualitative explanation that involved variations in negative and positive resistances in a tuned circuit. He pointed out that great amplification could be obtained if the negative resistance exceeded the positive resistance at periodic intervals so long as the average resistance remained positive. He credited his friend Alan Hazeltine for theoretical assistance.

Perceived as a solution to the problem of manufacturing low-cost but sensitive radio receivers, the superregenerative receiver soon attracted the attention of executives at RCA who saw it as a way to gain entry into the lower-price range of a rapidly expanding mass market. Armstrong received $200,000 in cash and 60,000 shares of RCA stock for rights to his superregeneration patents, thus becoming the corporation's largest individual stockholder. He was given an additional 20,000 shares for his assistance with the commercial superheterodyne-receiver design. His holdings of RCA stock eventually became worth approximately $9,000,000 so that he might have chosen to retire to a life of affluence by the time he was 35.

The superregenerative patents did not prove to be a wise investment for RCA since it did not provide adequate selectivity for closely spaced stations in the broadcast band although it did achieve some success in specialized high-frequency applications.

FREQUENCY MODULATION

The decade of the 1920s had been an age of super-power network proposals, superheterodyne, and superregeneration when Armstrong had skillfully exploited his opportunities. In contrast, the 1930s brought a severe economic depression, corporate retrenchment, and the birth of electronic television systems. It was an environment that still could provide opportunities for the independent inventor as demonstrated by the case of Philo T. Farnsworth. For Armstrong, the 1930s were filled with frustration in the courts and in the negative response of RCA to his efforts to promote the frequency-modulation broadcasting system that became his great obsession.

Late in 1933, Armstrong was issued a cluster of FM patents and conducted a demonstration of his system for David Sarnoff, of RCA. The following year, he was permitted to install an FM transmitter in the Empire State Building for tests that continued until April 1935. When it became clear that RCA intended to devote its resources to the development of electronic television rather than FM, Armstrong decided to use his own considerable resources to introduce the system that he was convinced would be far superior in quality to AM. For the first time, his activities would have to go beyong the stage of invention and even development to include marketing and lobbying. In brief, he would have to function as an inventor-entrepreneur rather than as an independent inventor relying on large corporations to convert his inventions to commercial products. To add further to the complexity of the challenge, he was trying to develop a complete system of transmitters and receivers for an uncertain market rather than components for an existing system as his earlier inventions had been. On the positive side, he still had access to laboratory facilities at Columbia and could afford to hire a staff of young engineering graduates to assist in development of the hardware. Filled with optimism after the first successful tests, he wrote in a log book that "after ten years of eclipse, my star is again rising."

Once again, Armstrong followed his earlier pattern by giving an IRE paper on FM in November 1935. He took obvious delight in pointing out that mathematical theorists had erred in dismissing FM as offering no advantages. He stated that he was introducing a "new principle" that conflicted "with one which has been a guide in the art for many years." Again he used no equations but relied on block, circuit, and phasor diagrams in his explanation. Nevertheless, the system he described was based on relatively unfamiliar concepts and the response of the profession was more subdued than it had been to his earlier professional papers. By 1936, he was realistic enough to acknowledge that the introduction of FM might be delayed by "intangible forces" originating in "vested interests, habits, customs and legislation."

As an integral part of his campaign, Armstrong installed an expensive FM transmitter in Alpine, NJ and began regular broadcasts in 1939. The same year, the so-called "Yankee Network" was formed to begin FM broadcasts from several sites in New England. Armstrong's system attracted the support of a large corporation when GE acquired a license to manufacture FM equipment and constructed an experimental station. E.F.W. Alexanderson, of GE, had visited the Alpine facility early in 1938 and had recommended that GE seize the opportunity that had been missed by RCA, and identify itself with a new system of high quality. In a 1940 paper, Armstrong compared the FM-AM situation to the battle between AC and DC power systems of the late 19th century. He predicted that an FM revolution would take place over the next five years and would largely supplant AM broadcasting. His aggressive crusade for FM was gaining considerable momentum when the second World War intervened.

Armstrong continued to receive professional recognition for his technical contributions including the Franklin Medal of the Franklin Institute in 1941, and the prestigious Edison Medal of the AIEE in 1943. During the Edison award ceremonies, he referred to patent litigation as the "bane of the inventor's existence" and likened it to "the serpent in the Garden of Eden." During the war years, he helped in the development of FM communication systems for military applications including two-way systems for Army tanks.

The post-war years brought increasing frustration to Armstrong as FM radio broadcasting suffered at least temporary setbacks. FCC decisions that were unsuccessfully opposed by Armstrong, forced FM to move to a higher frequency band and to operate at lower transmitter power than in the prewar period. In 1948, he brought suit against RCA for infringement of his FM patents but "pre-trial hearings" dragged on for five years placing severe strains on his financial resources. He refused overtures for an out-of-court settlement. The Armstrong tragedy ended in a climatic act on the night of January 31, 1954 in a fall from the 13th floor of his River House dwelling. Armstrong's inventive talents had flourished in the age of vacuum tubes, radio mania, and corporate competition but ultimately his personal characteristics made it difficult to adapt to an environment of regulation and litigation. He fell victim to the serpent that invaded his Garden of Eden.

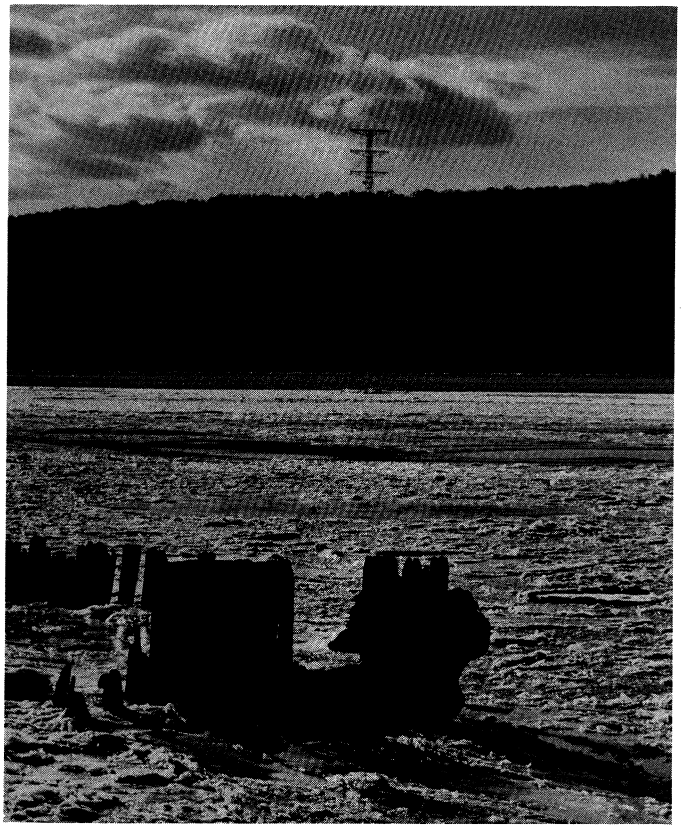
The Father of FM

—the tragic story of Major E. H. Armstrong

Jeanne Hammond

Atop the Palisades at Alpine, New Jersey, across the Hudson River from Yonkers, stands a tall,

Armstrong in WWI uniform. (Photo by Bradley B. Hammond)



Armstrong's radio tower atop the Palisades at Alpine, New Jersey, as seen from Yonkers. (Photo by Jeanne Hammond) three-armed tower. It is accepted as part of the landscape by those who live on the river's east bank and is seen daily by thousands of commuters on Conrail's Hudson Division trains, yet few know what this tower is or how it has affected their lives.

The tower and its accompanying radio station were built in 1938 at a cost of over $300,000 by Edwin Howard Armstrong, pioneer radio inventor, to demonstrate the superiority of his new system of radio broadcasting—frequency modulation (FM). After Promethean battles with the broadcasting industry, which fought to preserve its investment in the established system (amplitude modulation—AM), FM was finally accepted and today is the preferred system in radio, the required sound in TV, and the basis for mobile radio, microwave relay, and space communications.

As little known as the significance of the tower is the man who built it. Armstrong was born in New York City in 1890. When he was twelve years old, the family moved to 1032 Warburton Avenue—known to family and friends simply as "1032"—in Yonkers. The house, which still stands just up from the Greystone railroad station, was declared an historical landmark in 1978 by the Yonkers Historical Society.

Next door, on the north side of the house at the corner of Odell Avenue, was 1040 Warburton Avenue, the home of Armstrong's maternal grandparents. The members of the two families were a gregarious lot, and Howard's childhood was a happy one filled with large gatherings of relatives, many of whom were teachers. Learning was prized. "Quick, boy! How much is nine times five, minus three, divided by six, times two, plus nine?" His great uncle, Charles Hartman, principal of New York City Public School 160, would quiz his nephew to encourage his mental agility.

When Howard was fourteen years old, his father, who was American representative of the Oxford

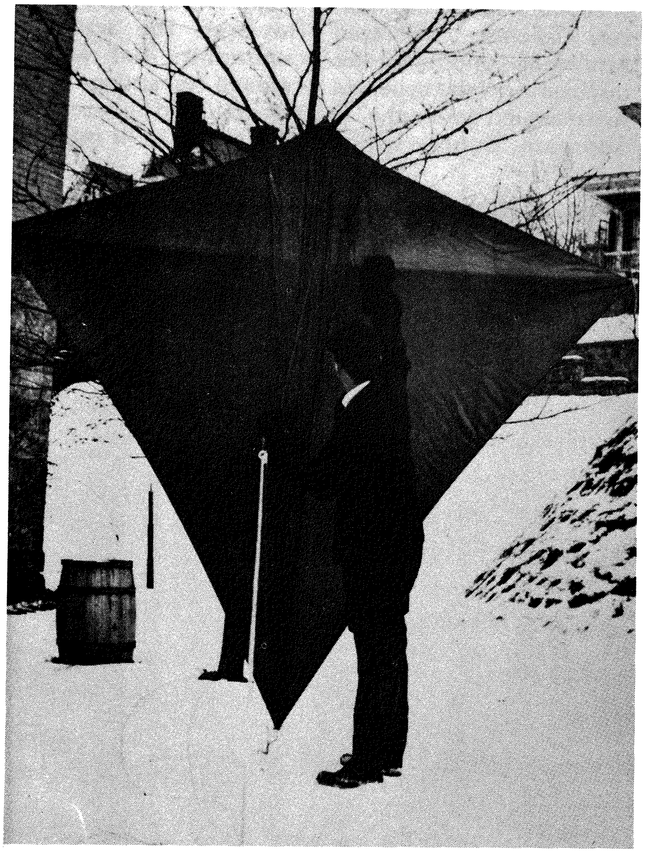
Howard Armstrong, about six years old, with his sister, Ethel.

1032 Warburton Avenue, Armstrong's boyhood home in Yonkers. His earliest experiments were carried out in the cupola on the third floor.

His bedroom/workroom in the cupola looked out on the spot on the Palisades where his radio station would later be. (Photo by Bradley B. Hammond)

University Press, bought him (on one of his yearly trips to London) a book, *The Boy's Book of Inventions.* Reading of Guglielmo Marconi's sending of the first wireless message across the Atlantic so excited his imagination that he determined then and there to become an inventor.

In his attic room in the cupola overlooking the Hudson River, Howard Armstrong began tinkering with radio. In those days, broadcast sound consisted of Morse code signals picked up with earphones. The incipient young inventor set out to make them louder. He was dogged in his search and developed at this early age a capacity for infinite patience in his experiments which was to mark his life's work. "Genius is one percent inspiration and ninety-nine percent perspiration," he



Armstrong constructed large antenna kites which he flew from the upper stories of "1032" in an attempt to improve reception.

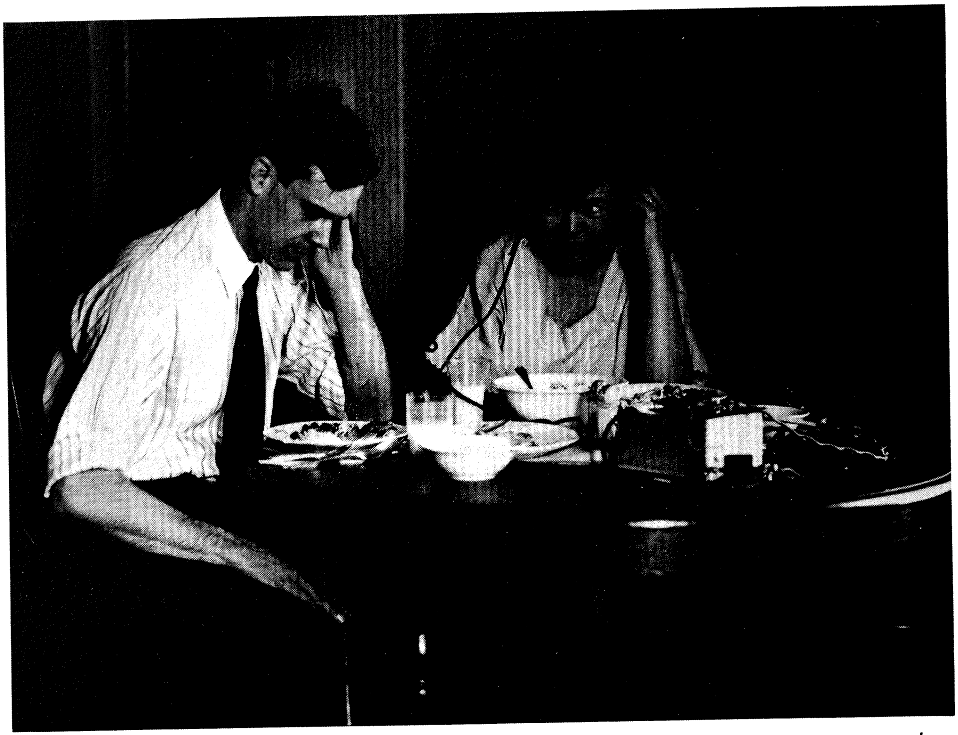
The young inventor at work on the "1032" pole.

used to say in later years, quoting Thomas Edison.

Armstrong explored many paths in his attempts to strengthen the sound. Reaching up into the air to better catch the broadcast signals, he flew from the upper stories of 1032 large antenna kites which he had built with the help of his Yonkers friend, Bill Russell. He built a 125-foot antenna pole, the tallest in the area, in the south yard. His younger sister, Edith ("Cricket"), helped in the construction, holding the guy wires and handing him buckets of paint as he swung aloft in a boatswain's chair. Neighbors watched with awe and apprehension. His mother, however, had complete faith in her son. When a neighbor telephoned to say that Howard was at the top of the pole and it made her nervous to watch, "Don't look, then," was her confident reply.

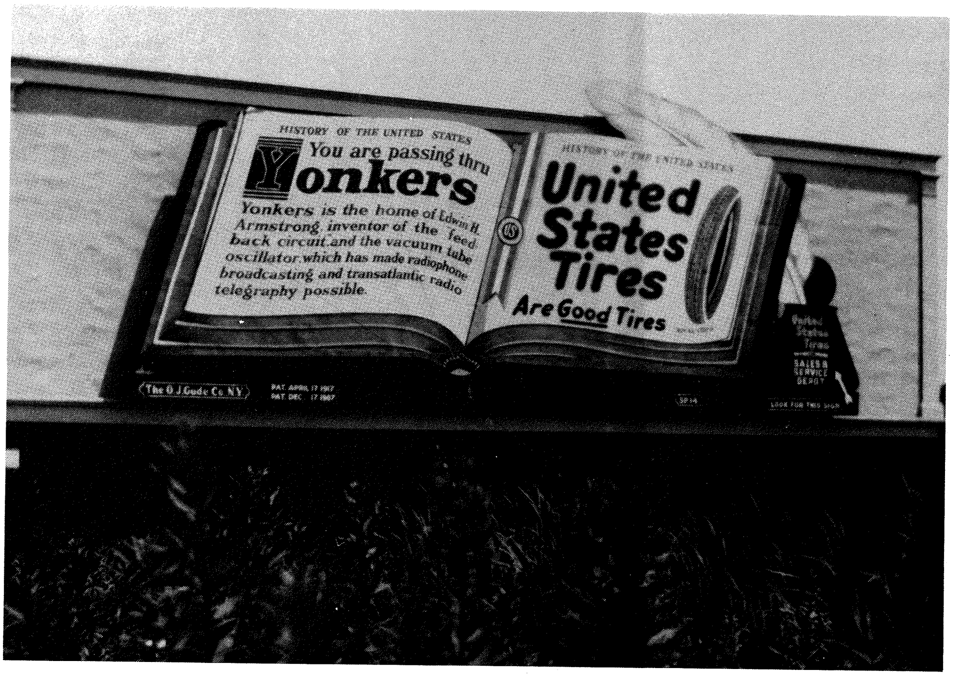
Howard attended Public School 6 in Yonkers and Yonkers High School, and went on from there to Columbia University, commuting on a red motorcycle his father had given him as a high school graduation present. His interest in radio led him to the study of electrical engineering.

In his junior year at Columbia, Armstrong's diligent search for improved radio reception paid off. He invented the regenerative-oscillating, or feedback, circuit which greatly increased radio signals, made them loud enough to be heard across a room and led the way to transatlantic radio telegraphy. His sister, Ethel, remembers vividly the night it happened. "Mother and Father were out playing cards with friends and I was fast asleep in bed. All of a sudden Howard burst into my room carrying a small box. He danced round and round the room shouting, 'I've done it! I've done it!' I really don't remember the sounds from the box. I was so groggy, just having been wakened. I just remember how excited he was."


Major Armstrong's sister, Ethel, and her husband, Bradley Hammond, listen to a crystal set with their evening meal, around 1920. (Photo by Bradley B. Hammond)

Later, another inventor, Lee DeForest, challenged Armstrong's priority for this discovery and the issue was twice argued before the US Supreme Court—which found in DeForest's favor. However, the scientific community has always credited Armstrong for the invention and he received a gold medal for it from the

Thomas J. Styles, Armstrong's longtime associate, Ethel, Howard, and his mother. (Photo by Bradley B. Hammond)


HISTORY OF THE UNITED STATES
You are passing thru
Yonkers
Yonkers is the home of Edwin H. Armstrong, inventor of the feed back circuit and the vacuum tube oscillator which has made radiophone broadcasting and transatlantic radio telegraphy possible.
United States Tires
Are Good Tires
The O.J.Gude Co N.Y.

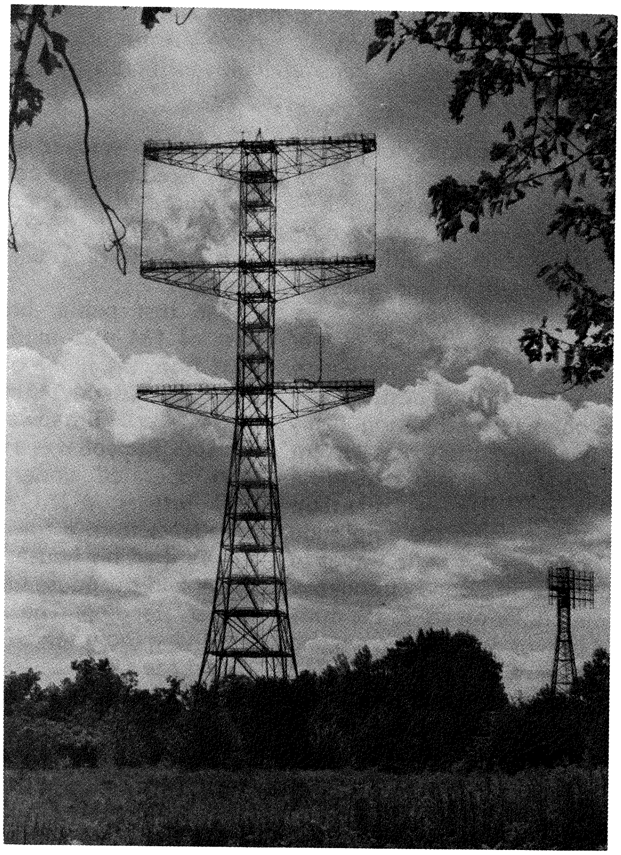
Billboard in Yonkers dating around 1921. (Photo by Bradley B. Hammond)

Armstrong and his wife, Marion, by the "1032" pole. (Photo by Bradley B. Hammond)

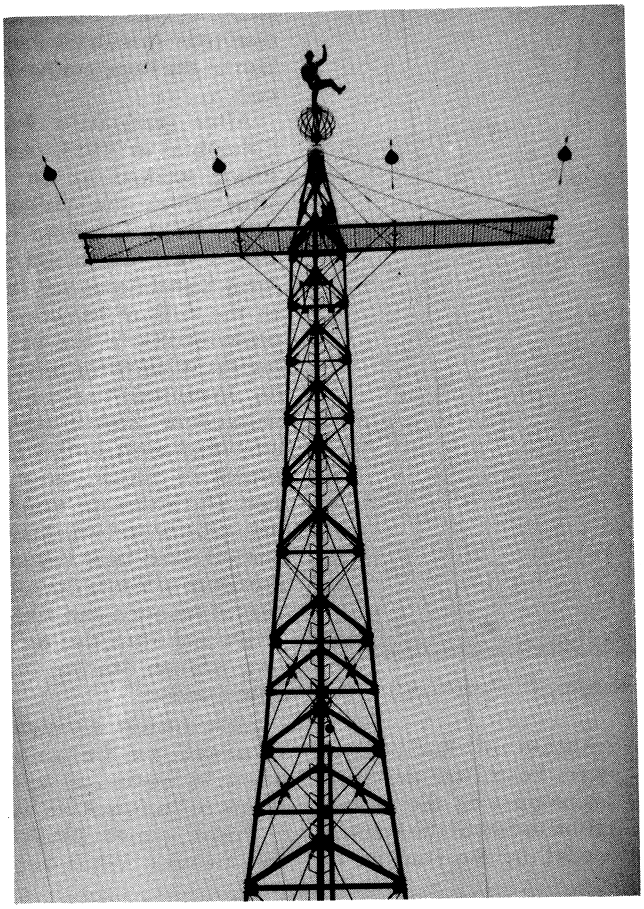
Institute of Radio Engineers. Years later, the report accompanying the presentation to him of the Franklin Medal, by the Franklin Institute in Philadelphia, also credited him with the invention of the regenerative circuit.

After graduation from Columbia in 1913, Armstrong worked as an instructor at the college. When the US entered the war in 1917, he joined the Army Signal Corps and rose to the rank of Major—his preferred title for the rest of his life. While in the service, he invented the superheterodyne circuit which amplified even further the sound of radio transmission. This invention brought him into contact with David Sarnoff, who later became President of Radio Corporation of America and whose bright and attractive secretary, Marion MacInnis, he later married.

After the war, Armstrong returned to Columbia where he worked as an assistant to Professor Michael I. Pupin, famed physicist and inventor. When Pupin



Close-up of the tower. (Photo by Bradley B. Hammond)



In 1923, to celebrate the opening of New York's first radio station—and to impress his fiancee—Armstrong cavorted atop the new WJZ transmitter tower. (Photo by George Burghard)

Armstrong receives the Medal of a Chevalier de la Legion d'Honneur *for his contributions to wartime wireless, from General Ferrie, head of French military communications.*

died, Armstrong took over his professorship and, financing his own research—his inventions had by now made him wealthy—concentrated on the elimination of static.

In 1933, Armstrong secured four patents which were to be the basis for frequency modulation. This was an entirely new system of broadcasting. Unlike amplitude modulation which varies the amplitude or power of radio waves to transmit sound, frequency modulation varies the number of waves per second over a wide band of frequencies. As static is transmitted by amplitude modulation and cannot break into the wide band of frequencies of frequency modulation, the latter is virtually static-free. Armstrong, who enjoyed aphorisms, liked to quote defeatists who said, "Static, like the poor, will always be with us." He proved them wrong.

The first public broadcast of FM was made in 1935 from the home of his friend C.R. (Randy) Runyon at 544 North Broadway in Yonkers. Runyon was a ham who operated under the call letters W2AG and broadcast from a tower in the yard of his house. The tower and the house are no longer standing. The Runyon living room served as a studio for a demonstration of different kinds of sound that were broadcast to a meeting of the Institute of Radio Engineers at the Engineer's Building on West 39th Street in New York City. Water was poured, paper was crumpled, and live and recorded music were beamed from the Runyon tower to the audience forty miles away.

Although the engineers marveled at the fidelity of the sound, FM did not immediately take off and it would be some time before it would become a commercial success. "If you build a better mousetrap the world doesn't necessarily beat a path to your door," Armstrong said ruefully in later years as he fought for the acceptance of his new system of broadcasting. As a matter of fact, FM was so revolutionary that an entire industry had to scrap its hardware and start over before its potential could be realized. Understandably, the establishment was less than enthusiastic at the prospect.

However, for several years RCA gave Armstrong experimental broadcast privileges in its studio at the top of the Empire State Building. But in 1937, saying that they wished to devote the space to the development of TV, they asked Armstrong to withdraw.

More determined than ever to prove the superiority of FM, Armstrong built his own station in Alpine, New Jersey. The site he chose had been visible to him as a boy from his attic cupola at 1032, and it served his purpose well. It was one of the highest

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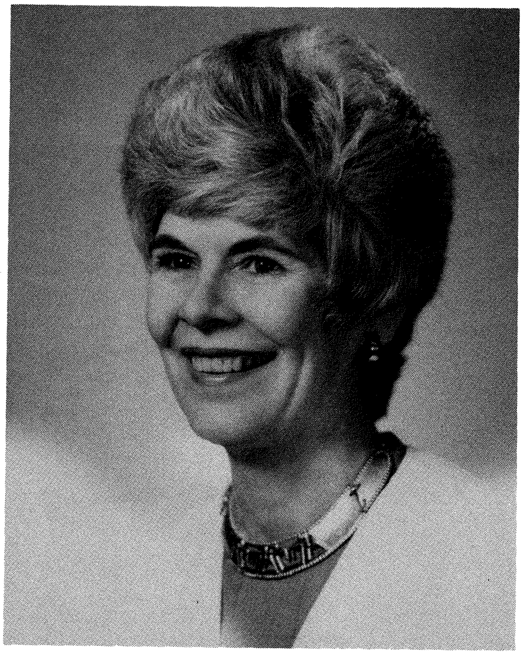
THE AUTHOR



Ms. Jeanne Hammond

The author, Ms. Jeanne Hammond, is the niece of the late Major Edwin Howard Armstrong.

points in the region and had unobstructed space around it for the broadcast of the station's signal.

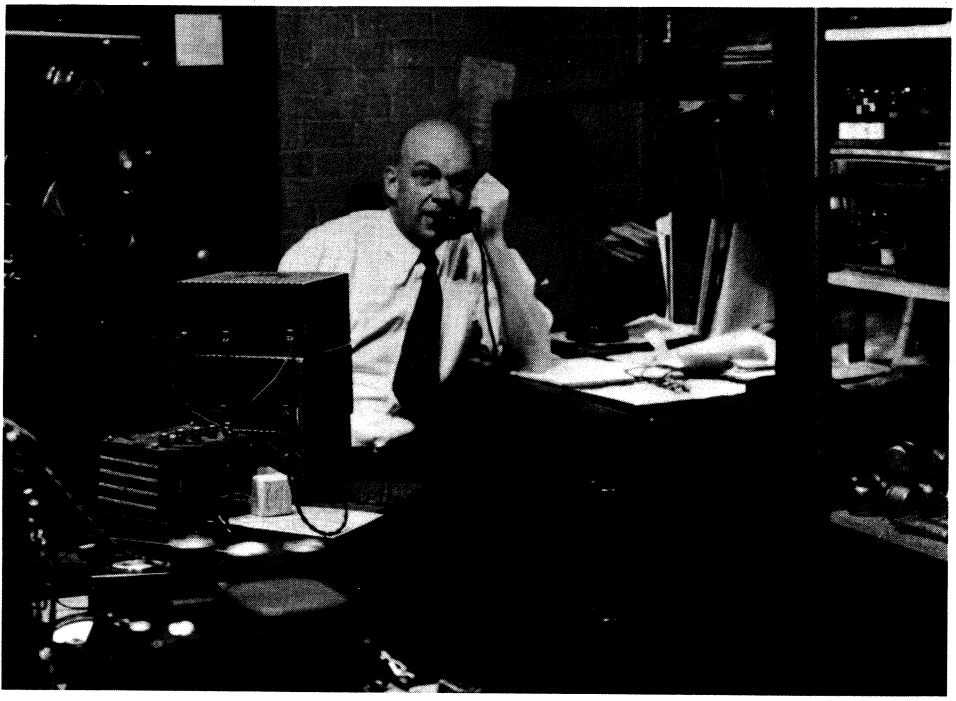
Programs originating with WQXR in New York City were transmitted by wire to Alpine and broadcast first under the call letters W2XMN and later, WE2XCC. Today, the station is owned by UA Columbia Cablevision Company of Oakland, New Jersey, and is operated for closed circuit TV transmission.

During the Second World War, Armstrong devoted himself to military research and allowed the government to use his patents royalty-free. He received the Medal of Merit for his contributions.

After the war, Armstrong turned his attention once more to the promotion of frequency modulation. He saw it grow in popularity as a broadcasting medium as more FM stations went on the air and more FM sets were sold to receive the programs. However, few outside the industry had ever heard of Edwin Howard Armstrong—the man who invented it. Furthermore, manufacturers began to build and sell FM equipment ignoring his patents. Goaded perhaps by the bitter memory of losing his regenerative patent years before, Armstrong became embroiled in twenty-one infringement actions to adjudicate his FM patents. Battling giant corporations with batteries of lawyers used up his resources. Finally, in 1954, ill, disillusioned, and his fortune gone, Armstrong took his own life.

After his death, his widow, Marion, set out to finish what he had started. She continued the lawsuits, sitting in the courtroom each day following the arguments and watching as testimony was given. Her first victory, over RCA in 1954, gave her funds to continue the other suits. In 1967, with the victory over Motorola, she had won all twenty-one and established clearly and decisively that Edwin Howard Armstrong was the inventor of frequency modulation.

Today, the Alpine tower stands as a monument to the brilliant man whose inventions touch our lives every day. His contributions are perhaps best summed up by Lawrence Lessing in his biography of Armstrong, *Man of High Fidelity* (J. B. Lippincott Company, Philadelphia and New York, 1956). "The lonely man listening to music in the night, the isolated farmer hearing nightly the news of the world, the airplane pilot guiding his craft safely through the ocean of the sky, the astronaut now in his capsule gathering in the whispers from space, the earthbound emergency crew contending with some mission of mercy or disaster, the army on the move and the man in his armchair, charmed or instructed for an hour by a great play, a symphony, a speech, a game of ball—all owe a debt to this man who, in some forty years of high fidelity, fashioned the instruments illimitably extending these powers of human communication."■



Armstrong at his desk at W2XMN.

THE ALPINE TOWER

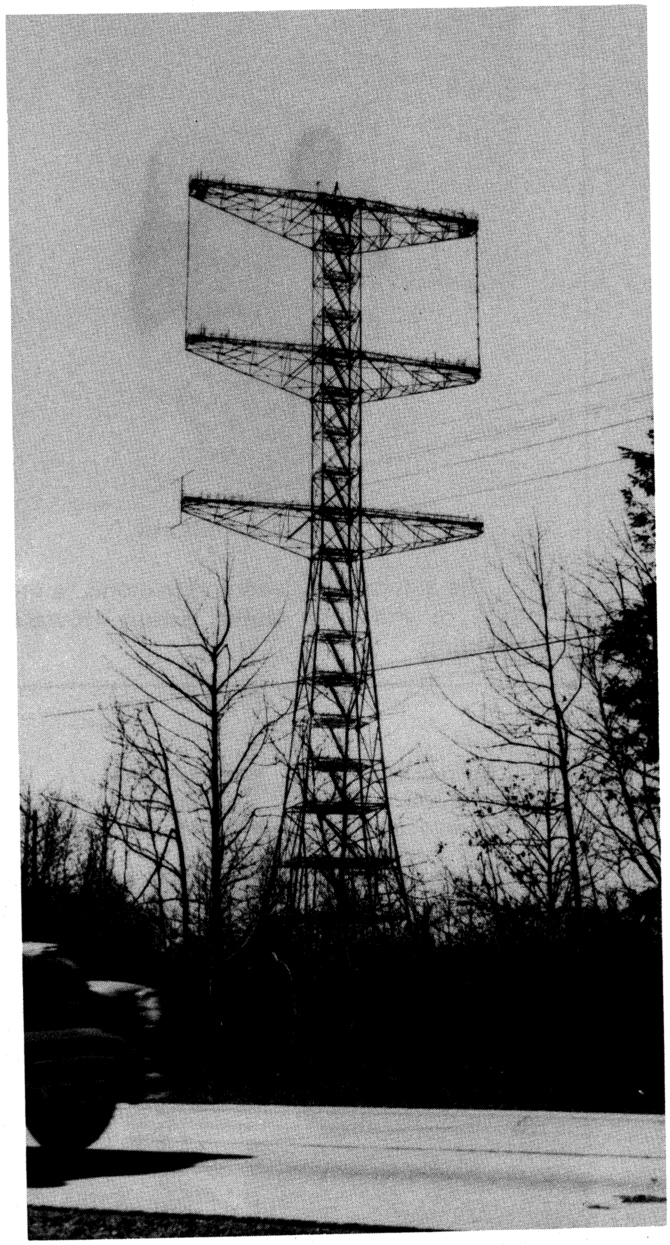
by **John T. Gubernard,** K2LSX

Atop the Hudson Palisades at Alpine, New Jersey, stands a tall, three-armed tower. Anyone who has ever traveled the Palisades Interstate Parkway through Alpine, has probably seen the huge structure. Few people are aware, however, that the structure now known as The Alpine Tower, was erected and completed by The American Bridge Company in 1938 for Edwin Howard Armstrong, pioneer radio inventor, to demonstrate his new method of radio broadcasting: Frequency Modulation (FM). Programs were broadcast at Alpine first under the call letters W2XMN and later KE2XCC. Armstrong's station KE2XCC went off the air on March 6, 1954 with the playing of his favorite music.

Some of the tower's specifications are:
Height above ground to top of third arm is 410 feet.
Height above ground to second arm is 320 feet.
Height above ground to first arm is 240 feet.
Height above sea level to third arm is 936 feet.

The tower, presently owned by the "Alpine Tower Company", is used for a wide variety of purposes including cable television by U.A. Columbia, for microwave transmissions by Eastern Microwave, for FM radio broadcasting by Fairleigh Dickinson University, and for two-way radio services by IBM, MCI, and Motorola. In addition, it is used by various governmental agencies. The tower site presently is being renovated due to the expanding complexities of the communication fields. However, none of the historic architecture will be changed.

Also located at the tower is the Major Armstrong Memorial Amateur Radio Club, Inc.", known as "MAMARC." The club was formed in May 1978 to encourage experimentation and development of new and little-used radio techniques -- in the pioneering spirit of Major Armstrong. The club means to assure that Armstrong is given his rightful place in history along with Marconi, deForest, and other radio pioneers. Edwin Howard Armstrong, who gave the world the static-free sound of FM radio, was amongst the last of the breed of attic inventors.



The Major Armstrong Memorial Radio Club, Inc. presently operates two repeaters at the tower site with operations on 446.525 MHz. and 223.680 MHz. The club also plans to assemble a museum at the site to display equipment used by Major Armstrong.

Creativity in Radio

Contributions of Major Edwin H. Armstrong*

By JOHN R. RAGAZZINI

Professor of Electrical Engineering, Columbia University

I

My purpose here today is to outline the contributions and to analyze some of the factors which have contributed to the creative genius of one of the great inventors of our time, Edwin Howard Armstrong. He would have been here today to speak for himself were it not for his tragic death some months ago. In discussing Major Armstrong, I may betray a certain amount of hero worship to which I freely confess for he was an heroic figure to all who knew him. In some ways, my speaking for him may give you a better picture than he would have been able to do for himself. Possessed of an innate modesty he probably would have minimized his role and personal contributions to the phenomenal series of inventions which have laid the foundations of modern radio communications. In referring to him I shall use the appellation of Major because he preferred it over others to which he was entitled.

To emphasize the importance of the contributions of Major Armstrong, I shall outline his inventions before going into his life, his times, his education and those personal characteristics which contributed to these successes. The four basic discoveries which represent his most important but by no means only creative contributions are the regenerative circuit, the superregenerative circuit, the superheterodyne receiver, and the broad-band frequency modulation system. These will be taken up in turn.

At the time of the invention of the three-element vacuum tube named the "audion" by Lee De Forest in 1906, radio communication, as we know it today, was launched. In those early days tubes were expensive and scarce and their characteristics none too favorable, so that it was imperative to increase the effectiveness of each individual tube. Setting the then accepted theories aside and embarking on an experimental approach, Major Armstrong was able in 1912 to obtain unheard of sensitivities from a single triode. While commonplace today, the concept of reinforcing a week input signal to the tube by feeding back a small portion of the output signal was revolutionary. He not only observed this phenomenon but was perceptive enough to realize its importance as an invention which he disclosed on January 31, 1913, and finally patented in 1914. The regenerative feedback circuit made possible communications across and between continents with a minimum of tubes.

Shortly after the initial disclosure of the regenerative principle for use as a sensitive receiving detector, Major Armstrong discovered that by increasing the amount of feedback it was possible to cause self-oscillations in the circuit. The tremendous importance of this property was quickly evaluated by Armstrong because a technique for producing oscillation by this means would replace the older spark or arc transmitters then in use. He filed a separate patent application for this circuit, a factor which later cost him heavily in patent litigation. De Forest was able to win an interference suit in 1924 which resulted in the issuance of patents to himself for the oscillating audion and regenerative circuit and the rejection of Armstrong's application for a patent on the oscillator circuit. Ultimately, as late as 1934 and after long and expensive litigation, the Supreme Court upheld the contention that De Forest was the inventor of the regenerative circuit and oscillator although the engineering and scientific societies, including the American Institute of Electrical Engineers, the Institute of Radio Engineers, and the Franklin Institute, generally discredited this decision by awarding medals and honors to Armstrong for his inventions including the regenerative circuit.

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* Presented at the Annual Meeting of ASEE, University of Illinois, June 16, 1954.

These brief references to Armstrong's patent litigation are cited not so much for their importance to the purpose at hand but to emphasize early in this talk a facet of his character which led him to fight tenaciously for what he considered to be right. This he did even when it cost him heavily and when he might have benefited financially by accepting an adverse decision. His lifetime will show many other instances of this characteristic.

Superheterodyne Reception

Chronologically, the second of his great discoveries was the system of superheterodyne reception. The first in the sequence of events leading to this invention was, the heterodyne principle which he studied experimentally and presented in his outstanding paper before the Institute of Radio Engineers in 1916. This paper laid the foundations for the future by rationally explaining the phenomenon of beating two high frequency inaudible signals to obtain an audible difference frequency signal. During World War I, the principle of superheterodyne reception was synthesized as a result of speculation on his part that attacking German bombers could be fired upon more accurately if they could be located by picking up the radiation from their ignition systems. The frequency content of this radiation was very high for those days and could not be picked up by then existing methods. The whole concept suddenly occurred to Armstrong that if he could reduce the frequency of the short waves to a value more manageable for amplification, receivers of much higher sensitivity could be designed. In retrospect, this seems to be a natural outgrowth of his early studies in the field of heterodyne detection. In his 1916 paper, Armstrong was dealing with the reduction of the frequency of a received signal from a high inaudible frequency, say 100 kilocycles to an audible frequency of, say 1 kilocycle, by beating with a local signal at 99 kilocycles. The principle was extended to take a very high radio frequency, say 10 megacycles and beat it down to an intermediate but inaudible frequency of say 150 kilocycles, amplifying at this frequency and then detecting the audible signal in this amplified signal. This invention was not used for its original purpose in World War I but it did become the basis for practically all radio reception including radar. It is interesting to note that the circle was completed only in World War II when radar detection of enemy aircraft came into its own using, a reception technique invented by Armstrong for the same purpose more than twenty years earlier. It can truly be said that the invention of the superheterodyne receiver represents a superb exhibition of inventive genius where one step logically led to another and a set of unrelated facts were synthesized into a useful device.

Shortly after his return from World War I, Major Armstrong became involved in the first of a series of court suits in defence of his patents. It was while carrying out an experiment at Columbia University to prove convincingly that statements made by opposing counsel were in denial of fundamental truths that he came upon the principle of superregeneration. While testing a regenerative circuit using a miniature transmitter located across the room without an antenna, he noted strange signals coming in with unbelievable signal strengths. Numerous transmitting stations were identified and their signal strengths were far beyond those observed in previous regenerative receiver tests. Far from ignoring this effect, he tenaciously studied it and finally brought to light a new principle of regeneration. What had happened was that the regenerative detector was being triggered on and off oscillation at an inaudible rate so that on the average, the circuit was being operated at a condition of tremendous gain located near the point of incipient oscillation. It was his ability to recognize that he had found a basic and important new principle that accentuated his genius, for it must have been true that many other experimenters had noted the effect previously. As a matter of fact, Armstrong himself came upon some old notes indicating that he had produced superregeneration in his early experiments many years before but failed to recognize it. This is a lesson that he never forgot and one which made him emphasize his persistence and care in experimentation lest unusual phenomena should go by without being noticed.

Frequency Modulation

Major Armstrong's final important invention was that of static-free frequency modulation reception known as FM. Ever since his early days with Pupin at Columbia, he had dreamed of the day when static, that is natural and man-made electromagnetic disturbances, would be overcome and useful signals could be received clearly and with high fidelity at all times. The basic technique used by Armstrong to solve this problem was to employ a system of modulation in which the intelligence was applied to a carrier signal by varying its frequency. This idea was by no means new, having been considered by numerous authorities in the field and having been discarded as impractical and as having no particular advantage over the current amplitude modulation system (AM).

In particular, expert opinion of the day was that the comparison between FM and AM based on both theory and experiment indicated no particular advantages for FM. This situation would have been enough to discourage any investigator from going much further. However, Major Armstrong had other ideas. He studied some of his concepts developed as far back as 1915 which led him to believe that broad-band, not narrow-band FM was the key to the problem. In view of the fact that the energy of the random noise or disturbances admitted into a circuit is proportional to its bandwidth, his notions seemed completely contrary to accepted concepts. The only trouble was that these concepts, correct as they were, were being applied to only one form of FM and did not reckon with the basic element in the Armstrong system which included the amplitude limiter. This device clipped off all amplitude variations superposed on the signal by unwanted static and permitted only the desired frequency variations containing the intelligence to pass through. The broader the frequency swing of the desired signal, the less significant would be the undesired swings due to noise. It was simply a case of the right theory being applied to the wrong model and again Armstrong proved that he was by far a more precise mathematical thinker even though he did not indulge in the writing of mathematical relationships.

In any case, the broad-band FM system including the all-important amplitude limiter was patented in 1933. This invention made possible the reception of almost completely static-free signals even in the midst of violent thunderstorms in the immediate vicinity, and this was indeed a technological triumph. Accompanying this great advantage was that of high fidelity made possible by the broader bandwidth employed by the system. Also, it was possible to prevent interference between adjacent stations since the Armstrong system caused the weaker station to be completely suppressed. By employing higher carrier frequencies he opened up a new large piece of the frequency spectrum to broadcasting. Finally, the cost of construction and operation of FM stations was less than that of AM stations with the same coverage.

Conflict of Interests

However, it was one thing to achieve this tremendous success and still another to bring about its acceptance by the broadcasting industry and the government. The conflict of interests between established organizations, like the Radio Corporation of America, and Major Armstrong had begun in all seriousness. The fight to bring about adoption of this, his greatest invention, consumed so much of Major Armstrong's time and energy that he was diverted from his primary activity of study and experimentation. FM proved to be the last of his great inventions and most of his activities from the issuance of the FM patent to the time of his tragic death were directed to the fight for adoption of FM. His devotion to this task proved to be so intense that his FM fight has often been referred to as his Cause. He was cast in the role of the lone inventor pitted against the array of great corporations that characterize our economy. In this task he was as dogged, as brilliant and as assured as he had ever been in ferreting out an interesting and peculiar phenomenon in the laboratory.

This recital of the most important technical achievements of Major Armstrong is by no means complete. It has been given to bring into focus the magnitude of his creativity and life-long achievement and to provide the framework into which to attempt to fit the human being that was Major Armstrong. The remainder of this discussion will be devoted to an attempt to explain the factors which contributed to his amazing record.

II

Edwin H. Armstrong was born in 1890 and spent much of his youth in the city of Yonkers, which as you probably know lies adjacent to New York City. While not wealthy, his family lived comfortably, his father being United States representative of the Oxford University Press. In view of his father's position it is not surprising that he was an avid reader of books, a factor that influenced the course of his life. That his preferred reading dealt with the lives of such great inventors as Volta, Hertz and Marconi was significant. One of his favorite idols was Faraday whose accomplishments he rivalled in later life. During his teens Armstrong filled his attic room in the Armstrong house in Yonkers with all the paraphernalia of the typical radio ham, including various wireless contraptions such as coherers, interrupters and spark coils of the day. Most of his spare time was spent listening to the dots and dashes of other radio hams in Yonkers and vicinity and occasionally picking up Naval and commercial stations both near and far. By the age of 19 Armstrong was ready to enter college and the maturing of the amateur into the professional had begun. It is important to note than even before entering college he had decided with typical singlemindedness to become an inventor in the field of radio and never to the day of his death did he waver from that objective. This man was no confused uncertain young teenager who had to have someone else make up his mind for him!

In 1909 Armstrong entered Columbia University to study electrical engineering and came under the influence of the great inventor and teacher, Michael Pupin, who was then Professor of Electrical Engineering. It was soon evident that, aided by formal training in electrical engineering, he had developed a knowledge of radio which far exceeded that contained in the textbooks of the day or, for that matter, of many of his instructors. His outstanding performance in this regard led him to study the performance of the then new and revolutionary De Forest audion while still a college junior. His experimentation resulted, as noted before, in the invention of the regenerative detector in the year 1912.

Scientific Turn of Mind

It is important to observe that a major technical contribution made by Armstrong about this time was not just the regenerative circuit itself which was an invention of first rank but also the explanation of the operation of the triode vacuum tube. Until then, it had been regarded as a trigger device, but Armstrong, with typical clarity and logic showed that its performance could be explained by the use of a characteristic curve and laid the groundwork for the vacuum tube circuit theory of today. This illustrates a scientific turn of mind possessed by very few undergraduate students today.

One might be tempted to conclude that Armstrong was a bookworm or possibly a "lab-worm" who paid little or no attention to other aspects of student life. Nothing could be further from the truth. While in college he rode, somewhat recklessly it is said, the hot-rod of his day—a red Indian motorcycle. He entered the usual freshman-sophomore contests and became a tough competitor on the tennis court. The latter sport was one of his favorites and he played well until he sustained an injury to his shoulder in later life. Nevertheless, despite these recreations, Armstrong never wavered from his primary objective, radio. By the time he was a college senior, Armstrong had a basic invention and the benefit of association with Pupin, a foremost inventor in his own right.

Because of his intense interest in his subject and because laboratory facilities would be available to him, Armstrong accepted an assistantship at Columbia University where he continued his work. His salary was quite low, only $50.00 a month, and I have often heard him relate how he used to have his one meal a day at a small restaurant on Broadway near the University because the proprietor was so foolish as to allow him all the bread he could eat with his meal. Not long after his acceptance of this post at the University, his regenerative patent issued and royalties began to pour in at the rate of about $8000 per year.

One might note here that the excellent guidance he received from Pupin and his associates on the management of his affairs as an independent inventor may have laid the seeds of much unhappiness and frustration in later years. Had he renounced all commercial advantage or financial return as his idol Faraday, his creativity might have been even greater because much of the energy he diverted to court actions and litigation would have been available for scientific work. But such was not to be, and much of Major Armstrong's life was spent in the defence of his rights as he saw them. It is interesting to note, however, Armstrong never relinquished his interest in or association with Columbia University and its freedom of thought and investigation, taking over and holding until his death Pupin's chair in electrical engineering. He was always the serious-minded, thorough, experimental scientist.

World War I found Armstrong in uniform as a captain in the Signal Corps. Whoever was responsible for assignment of personnel at that time should be congratulated for having placed Captain Armstrong in a position where he could help solve the problems of communications from ground to aircraft and many other similar problems in which he was a foremost expert. It was in this service that the inspiration for the superheterodyne receiver came to him. Discharged as a Major, he returned to Columbia to resume his life as a scientist and inventor.

Court Clashes

Once back, Armstrong entered into the first of his many court clashes in defence of his patents. The whole question of the regenerative circuit and oscillator against De Forest came up and during the proceedings, Armstrong was made an offer of $335,000 by Westinghouse Company for his regenerative and superheterodyne patent rights. In the meantime, he returned to his work on static elimination with Pupin and accidentally discovered, as described previously, the principle of superregeneration. Concurrently, he participated in the series of tests in 1921 sponsored by the American Radio Relay League which resulted in the successful communication between the United States and England on so called short wave transmissions at a wavelength of about 200 meters. It is significant to note that his colleague, Paul Godley, who picked up the signal in Scotland, used a superheterodyne receiver. Shortly after these tests his superregenerative patent issued, and by 1922 he negotiated with the Radio Corporation of America who wished to buy the rights. Negotiations were completed resulting in the payment to Armstrong of $200,000 in cash and 60,000 shares of RCA stock. This block of stock, combined with 20,000 additional shares for later services, made Armstrong one of the largest stockholders of the growing company. Financially, Armstrong was a multi-millionaire but this made little or no difference to his devotion to radio and his quest for static-free reception.

As a result of many visits to David Sarnoff's office at RCA, he met and courted Sarnoff's secretary, Miss Mac Innes. During this period he lost no opportunity to impress her with feats that were often quite daring and which reflected a bold and boyish personality. The most memorable of these was his hand-over-hand climb of the 400 foot tower of radio station WJZ. When he reached the top he stopped to pose for photographers. Whether or not this had any significant effect on his courtship is hard to say. At any rate, he and Miss Mac Innes were married in 1923.

Shortly after his marriage, Armstrong resumed his series of experiments at Columbia, which culminated in the invention of wide-band FM in 1932 with the patent issuing a year later. It was the fight for adoption of FM which constituted his most bitter series of disappointments. Armstrong tried to interest RCA in his new invention but for reasons which can only be speculative, but which involved the problems of existing investments, the coming of television and possibly personal relationships, he was rebuffed in a manner which offended Armstrong's sense of fair play. At any rate, it may be said that he declared war on RCA to the extent of turning down in 1940 an offer of 1 million dollars for a royalty-free license. The concurrent fight for broadcasting allocations was carried to the Federal Communications Commission where Armstrong finally obtained the allotment of a band in the 40 megacycle range for FM broadcasting. After the war, despite the fact that 500,000 sets were thereby rendered obsolete, the FCC moved the FM band up to its present 100 Megacycle range. This dealt a hard blow to FM, but still it flourished so that by 1949 there were 600 stations on the air. Throughout this latter period, however, RCA was waging war on Armstrong's patent position and most set makers were not paying royalties to Armstrong but were using the so-called ratio detector based on patents held by RCA. Armstrong claimed that this was an infringement and brought suit. The suit was at the stage of pre-trial hearings at the time of his death.

Armstrong fought the battle for FM with the same tenacity he used when attacking his technical problems. Above all, he was outraged at what he considered unfair treatment by RCA, and this may have affected his better judgment so far as personal advantage was concerned. His wife and his colleagues would have wished him to retire and enjoy his remaining years surrounded by loyal friends and revered as elder statesman of radio. The fact that he continued his fight was characteristic of the dogged tenacity which was so essential to his success.

III

Let us try now to review the important characteristics which may have contributed to Major Armstrong's creativeness in research. First, and foremost, he possessed a genius and character which was God-given. Placed in exactly the same circumstances, only a very few human beings would have had the capacity to achieve a fraction of what Armstrong accomplished. He was single-minded in his objective in life. He was thorough, very hard-working and indefatigable. When asked how Armstrong managed to achieve what he did, one of his assistants stated that he was willing to spend 23 out of 24 hours of his day concentrating on radio. If ever there was an example which illustrated the cliche that creative research is only slightly inspiration and mostly perspiration, he was it. He would repeat an experiment over and over again with little or no regard of the hour until every peculiar effect was fully explained.

The second important factor in his life was the professional education which he received. While he no doubt benefited greatly from his amateur radio activities before entering college, it was his formal education which matured him professionally. In addition, he came under the influence of a foremost teacher, inventor, and scientist in Professor Pupin who earned the reverence of young Armstrong. By making laboratory facilities available to Armstrong, Pupin greatly furthered his productivity.

The third important factor was the timing of his career. The time was ripe for the exploitation of the vacuum tube. Great research organizations sponsored both by industry and government were not in existence and the individual inventor had a good chance to do significant work. The type of work done by Armstrong as an individual in the early decades of the twentieth century is done now by whole organizations of engineers and scientists. It is correct to state that Armstrong is probably the last as well as possibly the greatest individual American inventor.

Fantastic Capacity To Think In Physical Terms

The fourth factor was Armstrong's fantastic capacity to think in physical terms. It is often said that he was a non-mathematical thinker, but such a statement would have been challenged by Pupin. If by mathematics one means simply the formal writing of symbolic mathematical relationships between quantities, he was indeed non-mathematical. A striking characteristic of his papers is that they are generally devoid of any equations. However, if one means by mathematics the exact science of rigorously following one step of logic with another to describe the whole, not necessarily using symbolism, then Armstrong was a foremost applied mathematician. It has been said that he disdained and distrusted the mathematical approach. However, from personal experience I know that he had the highest regard and respect for those who used the mathematical approach. What he objected to was the use of mathematics for its own sake or the application of erudite mathematics to an incorrect physical model resulting in the prediction of an incorrect performance. He demonstrated this devastatingly with his invention of broadband FM. As an experimenter, Armstrong had the uncanny faculty of observing effects and then assembling them into a logical whole thereby producing a clear concise and correct picture of a particular phenomenon. He demonstrated this over and over again starting with his early description of the performance of the triode, explaining the phenomenon of heterodyne and finally predicting the effect of broadband FM on noise reduction.

The fifth factor of importance was his ability to inspire loyalty among his colleagues and assistants. Armstrong was recognized by all as an important figure. Yet he retained a modesty and self-effacing character which made all who knew him or worked for him respect and like him. I asked him on at least two occasions to tell me what it was that was responsible for his enormous productivity and success. The question embarrassed him and he evaded a direct answer by reciting certain factual occurrences in his professional life. Never did he play up in any way his personal role. Probably he did not really know exactly what it was that made him the great man he was. His generosity and loyalty towards those whom he felt dealt honestly with him was renowned. At the same time his tenacious opposition to those he felt did not was equally well known.

Youthfulness of Outlook

Lastly, a factor which undoubtedly contributed to Armstrong's productivity was a youthfulness of outlook, a boyish enthusiasm which is hard to define. It was brought out tangibly in a number of his more daring feats such as the memorable climb to the top of the WJZ tower, or his swinging at the top of his Alpine tower in a boatswain's chair to adjust the antenna feed for his FM station. More intangibly, it shone in his eyes when he talked about his work. I shall never forget my last meeting with the Major, some two months before he died. The occasion was dinner at his apartment to which I had been invited to meet a business acquaintance of his who had a research and development proposal which he thought might be of interest to me. The Major was in a good mood. Only occasionally did he show a few flashes of the loneliness which lifelong concentration on his work brought upon him. At the end of a most enjoyable evening, his other guest and I bade him good night in the foyer of his apartment. I clearly remember him as I shook his hand. He was tall, powerfully built, one shoulder drooping slightly, his head bald, smiling his typical crooked smile, and looking a bit tired. But the most striking thing of all was the characteristic twinkle in his eye which belied his age and was like that found in a young man looking forward to another exciting day. Perhaps this was the most important asset of them all.

Major Armstrong died on February 1st of this year. At the time of his death he was in the midst of his greatest battle for FM. Regardless of the rights or wrongs of this or any of his other conflicts, opponents as well as partisans will probably agree that Major Armstrong was the most important creative thinker and inventor of all time in the field of radio and that his passing marks not just the end of the life of a great man but also the end of an era.

He Gave a Lusty Voice to Radio

"The Regenerative Circuit Was Not an Invention, it Was a Discovery," says Edwin H. Armstrong. The Story of the Man Who Was Responsible for Regeneration, the Super-Heterodyne, and Super-Regeneration, Three of the Most Important Contributions to Radio Science

By MYRA MAY

IF YOU were asked to name the ten men who have contributed most to the progress of the twentieth century, you would unhesitatingly include the name of E. H. Armstrong in your list. To him is due the credit for having taken the feeble, piping voice of radio and transforming it into a lusty tenor that can be heard all over the world. Under his care the adolescent wireless grew to manhood and developed from a raw recruit into a grand opera singer.

At the age of twelve, Armstrong started out with the ambition to train the untamed radio, and so well has he realized his objective that at thirty-four, he is famous as the inventor of the regenerative, the super-heterodyne, and the super-regenerative circuits.

In appearance, he is tall with mild blue eyes, a bald head and the erect carriage of an army officer. He is ready to talk on anything but himself. To elicit such personal facts, you must consult the "old" members of the Radio Club who knew "Howard" when he was at college and was struggling to establish his claim to his regenerative circuit.

"I knew Howard back in 1911 when he first began his experiments," says George Eltz, head of the radio department of the Manhattan Electrical Supply Company and one of his cronies. "He never spoke of what he was doing and none of us presumed to try to find out. He had made so much more progress in radio than any of the rest of us, that we followed him blindly. What he did was right as far as we were concerned, and he was our arbiter on all questions of wireless. He was a senior at college the year I transferred from Stevens to Columbia, but although we rarely saw each other at school, we often met at the Club.

A RADIO CLUB GROUP

Armstrong was closely associated with the Radio Club of America members when still at college, and when struggling to establish his regeneration claim. George J. Eltz, jr., one of the oldest members of the Radio Club, and now a director, says that in the old days the members were all jealous of Armstrong, for he was the only member of the club who possessed more than one tube. The above picture is a recent one of some of the Radio Club members. The gentleman with his left-hand thumb in a vest pocket is Louis Gerard Pacent, a director and committee member. To his immediate right is Thomas J. Styles, while to *his* right is George E. Burghard. Edwin H. Armstrong is a director of the Radio Club of America

"I remember going to Howard's home in Yonkers, one day—I think it was about 1912—and having the greatest thrill of my life, for I heard Little Glace Bay station in Nova Scotia. Most of our spark sets were unable to exceed the record of fifty miles some one else had set, so I felt that I was present at an epoch-making event to hear that distance. At that time, long antennas were fashionable; the longer the antennas, the better we thought we could hear. Armstrong's antenna, therefore, was strung along an embankment one mile in each direction, and we used to gaze in mute envy at the thousands of feet of wire.

"We had still another reason for envy. Howard was the only boy in the club who had more than one tube. The rest of us were proud to own even one, but Howard had quite a collection with which he constantly experimented.

"At the top of the house, he had his radio room which is as full of junk to-day as it was in those college days when we used to stand over him, and wide-eyed, watch his experiments. To support his antenna, he built the tall mast which still stands in front of the house. That mast was a wonderful vantage point from which to see fires. When the alarm sounded in Yonkers, Howard would make a rush for his mast. He always was a remarkable climber and could hoist himself up its length in double quick time.

"He had a better understanding of wireless than any of the members, and all of us in the Radio Club of America were aware that he was far ahead of science, in his knowledge of the audion. The rest of us looked upon radio as a fascinating diversion to which we gave as much time as we could spare, but Howard devoted his whole life to it. Day and night he spent in the little room at the top of the house, where he experimented with his tubes and gadgets."

As a boy he was chiefly interested in reading.

"We couldn't make him go out and play with the other boys," his mother says. "He was always curled up, his head bent over some book. Someone gave him a copy of Marconi's treatises on wireless when he was about eleven, and after that Howard was a hopeless radio fan. He borrowed every volume on electricity the town libraries had, and he transformed his bedroom into a laboratory".

When I called on Mrs. Armstrong in Yonkers, she showed me the laboratory on the third floor. The room is undisturbed and just as it was when the boy used to make his experiments. A beautiful old secretary is piled high with weighty text books, a work table before the window is covered with early sets, variometers and bits of wire; even the floor is strewn with radio parts. In another corner, there is a heap of worn, discarded electric light bulbs while on the other side of the room, old storage batteries still stand guard over the models of armatures young Armstrong made when he was first in the grip of the electrical fever.

"By the time Howard was ready

for high school," his mother continues, "he had read all the available English texts on wireless. At that time the German books were considered the finest so he elected German at school. It was no easy matter for a thirteen-year-old boy to master a new language and understand the technical features which are difficult even in a native tongue, but he persevered. He reached the stage when he could read the German as simply as the English. Whenever he has a plan he wants to carry out, he goes through with it, no matter how many obstacles may stand in his way.

"I remember when he was about thirteen, his little sister wanted a doll's house so he took some old boards and constructed the frame work of a cottage. He didn't know anything about carpentry but he worked until he had made a satisfactory job. Then he cut in the doors, windows, and even the stairway. After the little house was built, he added the crowning touch by putting in electric lights. Every room had its fixtures, which were controlled by switches.

HE ERECTS HIS FIRST ANTENNA

BY THE time he had progressed far enough into radio to want his own antenna, several years had elapsed. His sister, however, was still mindful of the doll's house so she helped construct the mast. Her part in the building operations was to send up on a pulley whatever tools Howard needed. That mast was about 170 feet high, but Howard climbed up and down with the utmost ease. The neighbors used to phone me to request that I keep my son away from the mast as it made them nervous to see him at such a perilous height.

"Howard was just out of college when he made his first invention. He used to stay up late into the night testing his discoveries. The policeman on our block says that the light shining from the third floor windows was his friendly signal when he used to patrol his beat. Since his marriage Howard no longer lives at home, but he still uses his laboratory and comes once or twice a week to work in it."

When Armstrong was twelve years old, Marconi sent the famous letter "S" across the Atlantic and the school boy up in Yonkers immediately evinced a keen interest. He had been playing with electricity for more than a year but from that time on his future was all mapped out. He devoted his spare minutes from school to radio just as thousands of other boys were doing, but unlike these others, he was driven on by his determination to understand the miracles of radio. For the next eight years he continued studying his beloved subject with unabated zeal. It had become the biggest thing in his life.

LEE DE FOREST TWENTY ONE YEARS AGO

This snap of Dr. Lee DeForest was taken long before anybody had thought of regeneration. It dates back to 1905, and was taken before the Boulder, Colorado, station. The names of Armstrong and De Forest are always mentioned when one begins to list those who made great contributions to radio

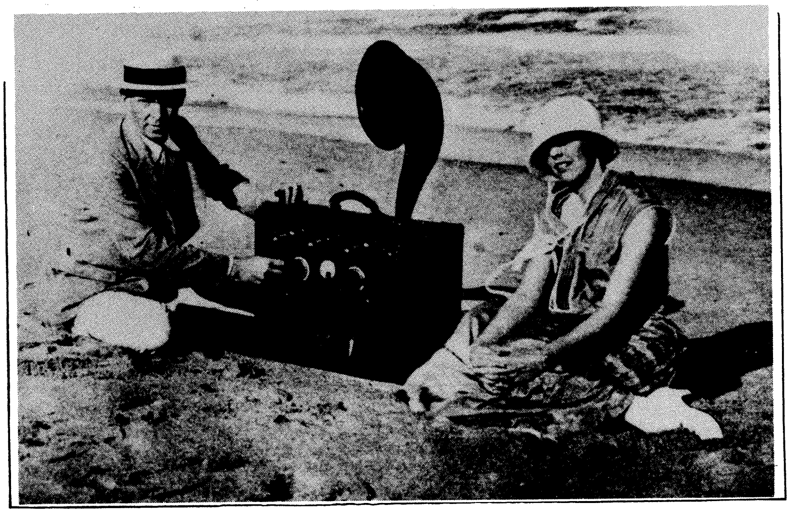
By chance he secured a De Forest audion tube. Nobody understood its mechanism but young Armstrong made up his mind that he was going to discover the laws that governed its operation. Hitherto he had been mastering the theory of wireless in a general way; now he had a definite task to accomplish. As a means to an end, he threw himself wholeheartedly into his college course of electric engineering. At home he experimented with his audion and tried out new ideas which were beginning to occur to him. It was not until three years later that he felt he understood his subject thoroughly and at that time, Professor Pupin declared that Armstrong knew more about the audion than any one else in the world.

He had simply put his mind on what he wanted and gone after it.

"The regenerative circuit," he explains, "was not an invention, it was a discovery. While I was working with the De Forest audion, I found in the plate circuit high frequency oscillations of perhaps 500,000 cycles where I had expected spark tone of only 1000 cycles to the second. According to our text books, these high-frequency oscillations should not have been there. Much excited, I tuned up the rest of the circuit so that it would be resonant with those waves. I was amazed at my discovery. Whereas a moment before the signals had come in faint and barely audible, they were now clear and strong and could be heard all over the house.

"As I listened in, I heard San Francisco and Honolulu faintly, signaling to each other. The two stations were about two thousand miles apart, but they were compelled to repeat their messages frequently while I, more than 5000 miles away, could clearly hear the whole proceedings. I did not, however, jump to any immediate conclusions. For the next couple of months, I checked up my discovery until I was very certain that it was genuine."

Then Armstrong invited his teacher, Professor Pupin, to hear the new circuit in operation. Astonished at what his pupil had done, Pupin told the chief engineer at the American Telephone and Telegraph Company about the boy's exploit. The engineer could not grasp the magnitude of the discovery and it was not until the next year that he

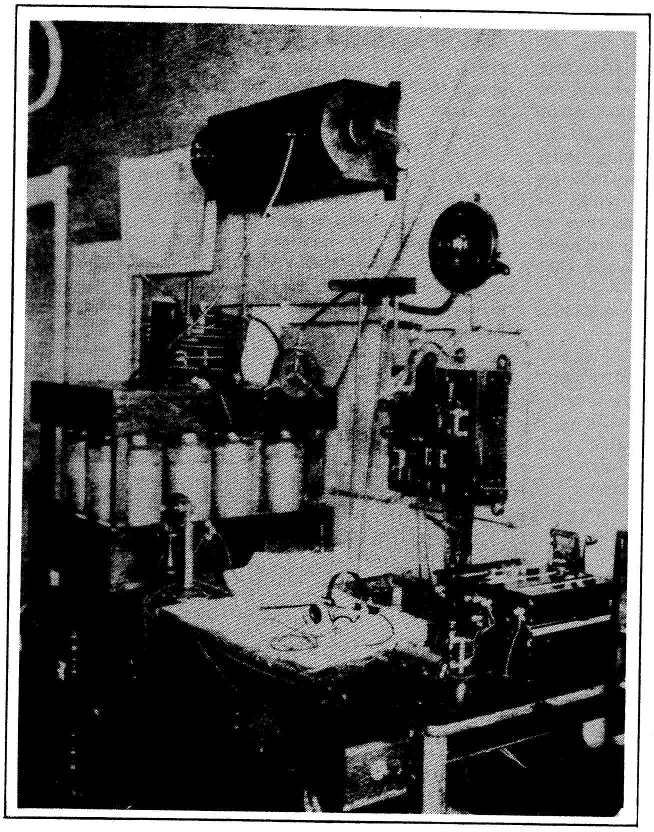


FAR FROM THE MADDING CROWD

Yet unwilling to divorce himself from radio altogether for even his vacation period. Major and Mrs. Armstrong, on the sands at Palm Beach, listen to what the Florida ether has to offer with one of Mr. Armstrong's own "supers" came to investigate just what this boy Armstrong had really done. He found the boy had made good his claims, and realized at once what this revolutionary thing would mean for radio.

Armstrong hooked up the set and let his father hear Ireland and Honolulu. Then he asked for the money to take out a patent, but his father refused on the ground that inventions would interfere with his son's studies. The boy, however, believed that he had a really valuable discovery and applied to an uncle for the money to establish his exclusive rights to his circuit.

The uncle, instead, gave his nephew some advice which in later years proved more valuable than any amount of money could have been. He told the boy to make a drawing of his invention and have it witnessed and dated by a notary public.



AN EFFICIENT INSTALLATION, OLD STYLE

It is a standard United Wireless station. The receiver consisted of a crystal detector in conjunction with an "efficient" three-slide solenoid inductance. The transmitter was powered from a 10-inch spark coil. The discovery of regeneration played no little part in making obsolete such installations as that pictured. It is surprising, though, how much some persevering operators used to get from their sets before the advent of the tube

DE FOREST OPPOSES PATENT RIGHTS

WHILE the patents for the discovery were pending, Armstrong became involved in a long tedious law suit. De Forest claimed that the regenerative circuit which was based on his audion, was an infringement of his patent. The boy, fresh from college, found himself in expensive litigation that cost thousands of dollars, dragged over six years, and that left him at its conclusion, a weary man.

The drawing of the circuit which his uncle had advised, figured largely in the case. In the interim, between the witnessing of the sketch and the trial, the notary had died. The other side brought signatures of the notary which were ornamented with fancy flourishes and curleycues whereas the signature on Armstrong's document was a plain simple piece of writing. Ugly rumors of forgery began to circulate, but Armstrong finally saved the day when he produced witnesses who proved that the notary had two signatures. The plain one which appeared on the circuit drawing, was the notary's ordinary handwriting and the highly ornate one was reserved for special occasions. The notary had evidently so lightly regarded the signing of the school boy's drawing that he had used the regular unembellished signature.

After that point had been cleared in Armstrong's favor, there yet remained the more important matter of priority. De Forest, the plaintiff, claimed that he had preceded Armstrong, whereupon the defendant brought his college friends into court and they testified to his having told them of the discovery. One boy even submitted a diary which in the year of 1912, bore the entry, "Armstrong told me he had a connection for intensifying sound."

To strengthen the case further, moreover, Armstrong rigged up a radio set which he brought into court and which he explained in simple, non-technical terms. During the day, he was engaged in the law suit while at night he constructed the sets with which he hoped to substantiate his claims. He was laboring under an immense financial, mental, and physical strain. No company was willing to buy his invention while the patent was opposed or until he had proven his rights, so he struggled on alone, finding the way more and more thorny. The case dragged on and then the United States entered the war. Armstrong's reputation was already established, so when he offered his services to the government, he was given the rank of captain and sent overseas as head of Radio Communication. His was the most important wireless work in the A. E. F. At first he was in England and later he was transferred to France where he associated with the biggest scientific figures in Europe, and was made a Chevalier of the Legion of Honor in recognition of his second invention, the super-heterodyne. During the war it was found that the Germans, who had radio stations about a mile or two apart, sent signals which our wireless operators were unable to pick up. These signals were no longer audible when our stations, ten miles away, tried to receive them. Of course it was of the utmost importance for this country to be able to intercept enemy messages, but their transmissions were on very short waves, somewhere in the neighborhood of 3,000,000 cycles a second. Armstrong's problem was to amplify these high frequency oscillations so that they could be heard in the American stations ten miles back.

The vacuum tubes constructed in the United States failed to solve this outstanding difficulty that confronted the A.E.F.," he relates. "We were unable to receive extremely weak signals of frequencies varying from about 500,000 to 3,000,000 cycles with an absolute minimum of adjustments to enable rapid change of wavelength. Round in England and Latour in France had produced aperiodic radio frequency amplifiers covering the band from 500,000 to 2,000,000 cycles. Their results had been accomplished by the use of vacuum tubes and transformers of minimum capacity.

NECESSITY THE MOTHER OF INVENTION

WHEN the United States entered the war, the fact that it was necessary to produce extremely sensitive receivers for short wavelengths, and that tube capacity would prove a bar to a straightforward solution of the problem, was not known in this country. As a result, no attention was paid to the capacity in the type of the vacuum tube which was adopted, and while it met the requirements of the lower frequencies admirably, it was impossible to use it effectively for the frequencies of importance in the direction-finding service.

During the early part of 1918, through the courtesy and energy of General Ferrié and his staff, the Americans were supplied with apparatus of French manufacture.

It was apparent, however, that this source of supply could not be a permanent one and a solution of the problem became essential.

After much experimenting, the super-heterodyne was made for direction finding. It was Armstrong's first invention born of bitter need; the regenerative circuit had been the result of an amateur wireless operator's love of his work. The super-heterodyne was this wireless operator's reaction to necessity.

Harry Houck, who was Armstrong's sergeant in France, tells this story:

"The first super-heterodyne was developed under shell fire. They (Big Berthas) were bombing Paris and every few minutes another terrible explosion would shake our laboratory and add zest to our experiments. I had been working under a captain by the name of Armstrong for the past three months, and, while we conducted our research to the tune of exploding shells, I chatted with a mechanic about what a fine, straightforward chap this Armstrong was.

"'You know who he is?', the mechanic asked.

"Then for the first time, I learned that my superior officer was the Armstrong of regenerative circuit fame, the man who had been my secret idol since I was twelve years old. I could not believe that this unassuming Captain Armstrong was the famous man about whose inventions I had read so much. I had to be reassured by the men in the laboratory before I was convinced.

"The first set we made was a combination of parts from every type of radio in existence. We used old German apparatus that had been captured and sent to us for observation and we picked to pieces some of the American products also. Thus we gradually evolved our trial set. We sent it up to the front where it was an immediate success. From that time on, we intercepted German messages without difficulty. Every day brought new confirmation of the power of the super-heterodyne. We would hear that the Germans expected to attack a certain sector; we would decode a message from their air force; we would learn where they were massing their forces. Daily our set performed miracles, each of which was an exciting chapter in the story of the American Expeditionary Forces. Captures that formerly would have been outstanding events became such regular occurrences that we ceased to comment on them."

THE PHANTOM ZEPPELIN

CAPTAIN Armstrong became Major Armstrong, and he was made a Chevalier of the Legion of Honor, but he continued with unabated zeal to head the radio branch of the A.E.F. Part of his duties brought him in contact with airplane radio. He had to go up in the American planes that he might intercept the German messages which were sent between their Zeppelins and their ground stations.

On one occasion while Major Armstrong was up in the air, cruising around Paris, he and his pilot were startled by the sight of exploding shells dropping on the city below them. He was not equipped for aërial battle so he tried to locate the Zeppelins so that he could inform the American gunners below of their exact location. In vain he and the pilot sought some clue as to the whereabouts of the enemy machines.

"Those smart Germans must have made an invisible airship," the pilot said.

The invisible airship was wreaking more and more havoc. Buildings toppled, sirens whistled, shells exploded, and the Major could find no trace of the death-dealing "ship". It was not until Armstrong and his pilot returned to the hangar, that they learned the "invisible airship" was "Big Bertha" bombing Paris.

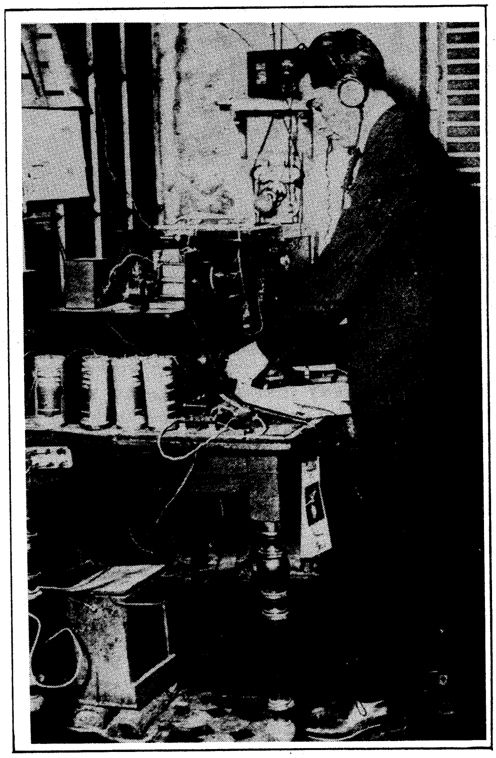
After the Armistice, American headquarters were moved to Spa, Belgium, to a house formerly occupied by Von Hindenburg. To keep in touch with the outside world, Major Armstrong set up a radio station in the cellar. He made a workable set out of the parts of a number of small damaged outfits. The very day that the new Spa station was in order, it was inaugurated by a message from the radio operator in Paris who explained that a cable for the Major had just arrived, and if he so desired, it could be transmitted by radio. The gist of the news was that the De Forest interests had reopened the legal fight in New York.

Armstrong was three thousand miles from home and his life's work was at stake. He reached home as soon as possible and resumed the long-fought battle. It dragged on until March, 1922, when a verdict in Armstrong's favor was at last handed down. Since then there have been additional legal engagements between the holders of the Armstrong patent and the De Forest interests. It is not, however, within the province of this article to go into the vagaries of the decisions and legal points involved.

During the experiments in court, with which he proved his case, he noticed the phenomena that led to the discovery of his super-regenerative circuit. It magnified sound enormously.

All three of his inventions, Armstrong sold to a large radio and electrical concern.

"Don't let the thought of money engross you; throw yourself into your work," he advises. "The best pay you can get is the satisfaction of a job well done, but society is so arranged that the man who has contributed happiness or comforts usually gets financially rewarded besides. Money comes to those who think little about the actual earning of the dollars and cents."



NORTH, SOUTH, EAST, WEST

Wherever radio has been taken up, the regeneration discoveries have been incorporated in amateur constructed receivers. This picture shows an Argentinian amateur operating his home-made receiver. The gentleman is Mr. D. S. P. Acuna, one of the best known of Argentinian radio enthusiasts.

EDWIN H. ARMSTRONG: AN INDIVIDUAL AGAINST A BUREAUCRACY

by **Benjamin S. Vickery**

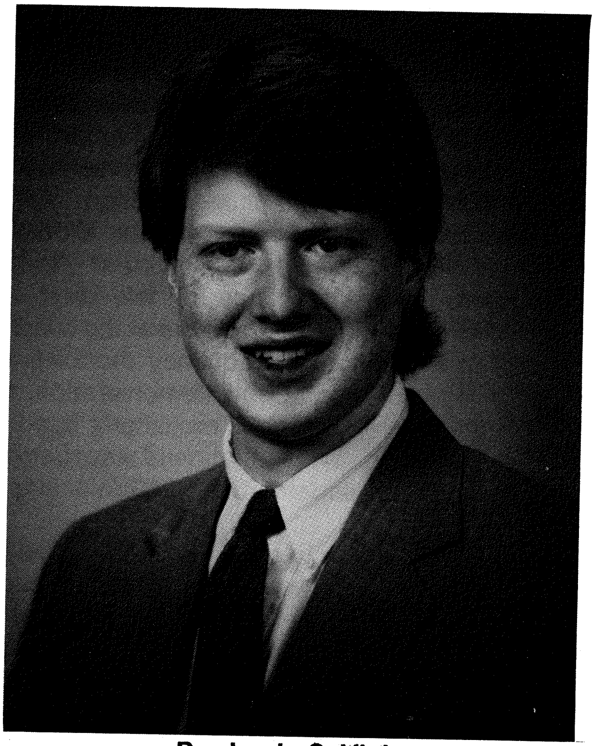
While Edwin Howard Armstrong made significant contributions in communications and electronics with inventions such as the regenerative circuit and the superheterodyne, his pioneering work in Frequency Modulation is considered his greatest achievement. His personal fight for the survival and growth of FM against a tide of bureaucracy and industry interests that had little to gain from FM, makes his role in FM radio's survival and success even more astonishing.

On November 20, 1940, more than five years after Edwin Armstrong's public unveiling of Frequency Modulation, General Electric's FM station, W2XDY, inaugurated commercial FM broadcasting. Among those present for the inaugural broadcast from Schnectady, New York, was George Henry Payne, Commissioner of the Federal Communications Commission, which had been born out of the Federal Radio Commission, created in 1927.[1] Brought into existence by the Communications Act on June 19, 1934, the FCC had been created for the purpose of communications regulation as well as for the protection and nurturing of the communications industry. As part of the first scheduled program broadcast over FM radio, Commissioner Payne delivered an address which celebrated both the invention and its inventor:

> "It gives me a particular feeling of pleasure to represent the Federal Communications Commission in such a tribute to Major Armstrong...I have seen how Major Armstrong, with great courage and tenacity of purpose, has consistently, in the face of strong opposition, carried his fight through to a successful conclusion." [2]

Payne's words were quite ironic in light of the fight to come between Armstrong and the FCC over frequency allocation for FM radio.

Armstrong's first encounter with the FCC on the subject of frequency allocation gave little hint of the adversarial relationship that was to develop between the Commission and the inventor. From June 15 through June 26, 1936, the FCC held an informal engineering hearing both for the review of existing frequency allocation below 30,000 kilohertz, and to determine upcoming needs for the allocation of frequencies above 30,000 kilohertz. Factions interested in the "very high frequency" (or VHF) range included police, government, military and emergency services, as well as the communications industry which included both commercial radio and experimental radio and television.[3] While most of the radio faction was dedicated to AM radio, two men -- Armstrong and Paul DeMars (who would later become chief engineer of the Yankee Network, a network of New England radio stations that began experimental FM broadcasts in the late 1930's) -- attended the conference as representatives of FM.



Benjamin S. Vickery

Armstrong had first demonstrated Frequency Modulation and its uses during the presentation of his paper entitled "A Method of Reducing Disturbances in Radio Signaling by a System of Frequency Modulation" before a meeting of the Institute of Radio Engineers on November 5, 1935.

Armstrong again demonstrated FM at the FCC hearing as he presented a sound-on-film recording of an AM versus FM reception comparison. The demonstration consisted of a comparison between FM signals transmitted from a two kilowatt transmitter at 41 megahertz from an antenna atop the Empire State Building, and AM signals broadcast from New York's 50 kilowatt station WEAF. Both signals were received in Haddonfield, New Jersey, some 85 miles distant. The demonstration showed FM's clear advantage in both sound quality and static noise reduction. Like Armstrong's first demonstration, his presentation before the FCC garnered little attention. It is interesting to note that a report on the allocation hearing in the FCC's *Second Annual Report* comments on the attendance of television and facsimile transmission experimenters at the hearing, but makes no mention of frequency modulation.[4] Still, as a result of Armstrong's demonstration, the FCC allocated the 42.5 to 43.5 megahertz band for FM experimentation. Within that band was room for five stations, each separated by 200 kilohertz or kilocycles.[5]

By late 1939, twenty experimental FM stations were in operation. Five stations operated under FCC licensing and fifteen stations were operating under FCC construction permits. Most stations were eager to make the switch to commercial broadcasting. The experimental nature of FM, and the lack of a regulated FM "industry" served to keep production of FM receivers low. It was estimated in late 1939 that only 2,000 - 5,000 FM receivers had been distributed and most of those receivers were concentrated in New York City and New England.[6] During December of 1939, in the face of a growing number of applications to begin commercial FM broadcasting, the FCC announced that an informal engineering hearing would be held on February 28, 1940 before the full Commission. The purpose of the hearing would be to determine a permanent policy "with respect to either or both systems of modulation on frequencies above 25,000 kilohertz for regular broadcasting services."[7]

Charges were made that the FCC was delaying the introduction of commercial FM. AM radio was still young and many considered it vulnerable to a new system of radio that could deliver better sound quality, less interference, no static, and the ability to broadcast over a greater area using the same amount of power. The industry's economic fears were concisely expressed in an October 1939 *Fortune* magazine article which began: "A fighting inventor [Armstrong] is in a position to cause replacement of 40,000,000 radio sets and $ 75,000,000 worth of broadcasting equipment."[8] Also, the FCC was hesitant to assign commercial frequency ranges because of the needs of another experimental form of broadcasting which the FCC felt could revolutionize the communications industry: television.

Finally, on March 18, 1940, amidst continuing charges of foot-dragging, the Commission began its frequency modulation hearing. Based on the evidence from two weeks of hearing, and staff investigations on frequency modulation, the FCC decided for the good of public interests that FM was ready for the establishment of commercial service. The FCC touched on the potential and growing practicality of FM in their May 20, 1940 frequency modulation report:

> "Frequency modulation is highly developed. It is ready to move forward on a broad scale and on a full commercial basis. On this point there is complete agreement amongst the engineers of both the manufacturing and the broadcasting industries. A substantial demand for FM (frequency modulation) trans- mitting stations for full operation exists today. A comparable public demand for receiving sets is predicted."[9]

The frequency band between 42 and 50 megahertz was assigned for commercial FM use, enough for 40 FM channels. Of the 40 available channels, 35 would be available for commercial use while five would be used for non-commercial educational broadcasts.[10] Commercial FM broadcasting was set to go into effect on January 1st of the new year, 1941. Unfortunately, Armstrong had little time to watch FM's commercial development before the second World War brought growth to a halt.

World War II impinged uniformly upon all "critical" industries. As a result, civilian production of the electronic equipment which fueled FM broadcasting stopped and, without it, construction of FM transmitters and receivers, in addition to the towers and other vital components of the FM industry, came to a halt. Although forty-odd FM stations, amongst them Armstrong's own Station W2XMN, continued to broadcast to their audience of roughly a half-million FM receiver owners, commercial FM stayed in a holding pattern for the next half-decade.[11]

Perhaps Armstrong himself best summed up the War's disruption of FM's potential when he said in 1944: "Eight years ago, I had the privilege of bringing to the attention of this Commission a new system of broadcasting which, I ventured to predict, would not merely supplement but rather would supersede the existing standard system...But for the advent of the war, it is a reasonable statement to make that this prediction would have been well underway to fulfillment. Beyond question, some hundreds of transmitters and a good many millions of receivers would have been operating in this country alone at the present time." [12]

Planning for post-war development did not come until Fall 1944 when it seemed finally that an end to the war might be just over the horizon. The FCC was to hold a hearing during October 1944 in Washington, DC for the purpose of determining post-war frequency allocations. Because of the expected increase of FM stations operating in post-war America, the FCC considered options which would allow a greater number of FM stations than the 40 station limit set by an 8 megahertz bandwidth comprised of channels set 200 kilohertz apart.

One option considered by the Commission was to shorten the width between channels from 200 to 100 kHz. In his testimony and cross-examination before the FCC hearing on October 12, Armstrong pointed out a number of problems with a reduction in channel width such as a significant increase in noise-voltage level and an increased chance of problems due to oscillator drift over a shorter frequency range. Additionally, Armstrong stated that reduction to a 100 kHz channel width would "make the use of any multiplexing service a practical impossibility."[13]

Another possibility, and a much more serious one, raised by the FCC was the relocation of FM to a higher range of frequencies than the 42-50 MHz range in which FM had been operating since 1940. It was during this October 1944 hearing that the FCC first "tipped its hand" in revealing a major aspect of a future strategy, aimed towards moving FM up to higher frequencies, and based upon dubious reasoning. Armstrong was asked for his judgment on interference levels in the 100 MHz range. Armstrong cautiously replied that interference at higher frequencies probably would be less, but also stated that he would rather deal with interference "head on" in FM's current bandwidth, rather than trying to escape a phenomenon that hadn't ever posed a real threat to FM transmissions in the 42-50 MHz bandwidth, by packing up and moving to an untested, higher frequency range. Indeed, when asked by the hearing Chairman what the major difficulty in a possible move to 100 MHz was, Armstrong stated that the principal worry to be the possibility of unexpected difficulties with the move to and operation in the higher frequency range. As FM's creator said, "There have been...occasions when FM escaped oblivion by a very narrow margin, and I wonder if it would not be tempting the gods to take it again." [14] It was obvious that any movement of FM out of its current frequency would make existing FM hardware, both on the part of the FM broadcaster and the FM receiver owner, obsolete. To force a fragile new medium of communication that had suffered through almost five years of stagnation to "start over" in many respects seemed too much to ask.

If there were any doubts that the FCC wanted to move commercial FM from its first and only home, they were erased with the January 15, 1945 issuing of proposed frequency allocations, which found FM moved up to double its then current frequency. This came after the Radio Technical Planning Board, or RTPB, recommended in October of 1944 that FM stay in its current frequency range of 42-50 MHz. Created by the FCC to represent industry as an authoritative voice in the hearings and chaired by Dr. W.R.G. Baker, the RTPB had organized a number of Panels. Each Panel was made up of industry "experts", and each Panel focused on a particular subject. Panels #5 and #2, focusing on FM broadcasting and frequency allocation, respectively, both concluded that FM should not be moved.[16]

The RTPB decided that about 75 FM channels, each 200 kHz wide, would be required to accommodate a national allocation of commercial and educational FM stations. Thus, the RTPB recommended, rather than moving FM, extending the FM frequency range down to 41 MHz and up to 56.[17] In a joint report, the two Panels stated that the issue of FM frequency allocation was the most important issue in the FCC proceeding, and that both Panels recommended that FM remain essentially where it was and expand around its current location. Furthermore, they reported that no other RTPB Panel had recommended otherwise.[18]

Additionally, the Interdependent Radio Advisory Committee (IRAC), representing government departments, drew up an allocation plan for the frequencies in question. Like the RTPB, the IRAC recommended that FM not be moved from its prewar position, just that it be allowed to expand around its narrow frequency range. Actually, the IRAC advised slightly less expansion of FM around its current band than the RTPB had, advocating an FM frequency range of 42-54 MHz.[19] So, both groups had recommended that FM expand around its 42-50 MHz range rather than be moved to an entirely new band. Why, then, did the FCC propose the exact opposite of both the RTPB's and IRAC's recommendations?

The official FCC reasoning for this move was based on predictions of "skywave interference" by Kenneth A. Norton, a former FCC engineer, ironically employed at the time of the hearings by one of Major Armstong's old employers, the U.S. Army Signal Corps.[20] Specifically, Norton considered three sources of interference significant enough to warrant a move to a much higher frequency range: tropospheric wave transmission, Sporadic E transmission and, most importantly, F2-layer transmission. In a brief presented before FCC Docket No. 6651, from February 28th to March 3rd, 1945, Armstrong discussed and, in the eyes of the industry, discredited Norton's findings.

Created by ionized sections of the earth's atmosphere, Sporadic E transmissions come from an intermediate level of the atmosphere. They can occur during light or darkness, and appear with greater frequency (no pun intended) during the summer. They are not affected by solar activity. Although they are portrayed as having the ability to severely disrupt FM broadcasting, Norton actually testified during the hearings that Sporadic E transmissions were for all practical purposes unimportant to FM broadcasting even at FM's current frequency band. Armstrong formed an analogy from Norton's testimony that illustrates the unimportance of Sporadic E transmissions when he said in his March 3rd brief, "Stated another way, Mr. Norton agreed that a station normally having a range of 120 miles would cover, without interference, a range of 100 of those miles 99.9% of the time, and that for 99.975% of the time, 80 miles of that range would be covered without interference." [21]

Tropospheric wave transmission is caused by the bending of waves within a few miles above the earth's surface. Like Sporadic E transmission, tropospheric waves seem to occur in both light and darkness, are prevalent during summer months, and seem unrelated to solar activity. As this form of interference was understood to a much lesser extent than Sporadic E transmissions and F2-layer transmissions, neither Armstrong nor Norton were able to determine the effect of this phenomenon. In fact, Norton seemed to imply the possibility of less tropospheric interference for lower frequencies when he testified: "As the frequency is increased, the tropospheric wave interference range maybe expected to increase."[22]

As the potentially most-severe form of interference, the F2-layer consists of the electrified strata of the upper atmosphere, or ionosphere, from approximately 225 to 400 kilometers above the surface of the earth. Reflections from this layer cause some interference at low-level frequencies during the three years of peak solar activity in the eleven year sunspot cycle. This F2-layer interference would manifest itself only during the middle of the day in winter months.[23] Using the last sunspot cycle between 1933 and 1944, Norton used a set of curves first presented to the Commission by Dr. L.P. Wheeler on October 24, 1944, which estimated the percentage of listening hours during which the F2-layer transmission, or interference, would occur. Ionospheric measurements that estimate worst-case conditions of potential interference were used. Norton's curves predicted F2-layer transmissions at levels up to and over 100 MHz whereas previous tests and observations from industry experts such as Dr. Harold Beverage, who had gathered data for Washington, DC, had never revealed F2-layer transmission above 60 MHz.[24] Characterized at the time as data from an undisclosed location, later declassification revealed that Norton had taken his data from the island of Maui. Based on his findings, Norton recommended that FM be reassigned to a frequency band above 120 MHz.[25]

A fundamental error that contributed to Norton's findings was his understanding of wave reflection. Norton assumed that all that was necessary for the transmission of a wave between two points on earth was the reflection of the wave in the ionosphere at a location equidistant from the two points. Thus, if Norton's assumption was true, only one reflection would be required for the transmission of waves regardless of distance traveled, and F2-layer transmissions would be scattered around the world during peak solar activity. Fortunately, this is not the case. Because, due to the curvature of the earth, the longest single wave reflection that can occur covers approximately 2,200 miles; waves must travel between two points farther apart through multiple reflections, or "hops."

Further, F2-layer transmission will occur only if conditions are right for F2-layer transmission at the final point of reflection before the wave's reception. Thus, it is important what conditions exist at the preceding points of reflection.[26] This rationale was explained by Armstrong in his brief before the FCC. As it turned out that Norton's data had come from Maui, more than one "hop" away from the continental U.S., his findings were entirely invalidated.

What was not disclosed until Fall 1945 was that secret hearings had taken place on March 12th and 13th of 1945, during which Armstrong had brought such errors to light. Furthermore, the FCC itself recognized errors in Norton's findings. For instance, it was determined by the FCC that F2-layer transmissions would exceed previous estimates such as Dr. Beverage's only by 7% as opposed to Norton's predictions of interference even at 120 MHz, double the interference cutoff frequency of previous studies.[27] Additionally, a cross-examination of Norton by Armstrong verified that Norton was aware of his erroneous information:

> **Major Armstrong:** Everybody is already agreed, I take it, that for interference to enter the United States, a line roughly 1,250 miles beyond our borders will determine whether or not interference gets into the country.
>
> **Mr. Norton:** Yes, that is correct.
>
> **Major Armstrong:** And unless the ionosphere 1,250 miles away supports transmission, then we need not worry about F2-layer interference.
>
> **Mr. Norton:** That is right.[28]

This exchange not only verifies Armstrong's earlier conclusions with respect to Norton's findings but also demonstrates Norton's realization of the falsity of his own predictions. Incredibly, with full knowledge of this erroneous information, the Commission suppressed its findings, and publicly continued to cite Norton's data as their basis for moving the FM band.[29]

Considering the FCC's apparent determination to move FM up the frequency band, it came as no real surprise when on June 27, 1945, the FCC ordered all FM broadcasts to be moved from the 42-50 MHz bandwidth to FM's new bandwidth between 88 and 106 MHz (the 106-108 MHz range was allocated to facsimile with the provision that the band could be used for FM in the future). The FCC's Eleventh Annual Report provided the "official" interpretation of the frequency allocation proceedings:

> For several years there had been concern that FM broadcasting in the vicinity of 50 megacycles would be subject to serious skywave interference...The Commission has been conducting a recording program for over 2 years, measuring the extent and intensity of skywave signals from existing FM stations; the data collected during this program served to emphasize the amount of interference that would be expected when a large number of FM stations were installed and in operation in the vicinity of 50 megacycles. There was divergence of opinion as to the expected amount and effect of skywave interference in the future, some believing that the characteristic of FM transmission and reception would serve to minimize the deleterious effects of skywave transmission, and others believing that the service would be severely degraded during summer seasons and during times of high sunspot activity...Many factors are involved in a decision of this nature including ground wave coverage, skywave interference, transmitting and receiving equipment, present investment, and other matters of a minor character. Based on the testimony and data before it, the Commission was convinced that a superior FM broadcast would be furnished by operation in the vicinity of 100 megacycles...[30]

The FCC's decision was quite unpopular among broadcasting and manufacturing industries. Hearings on a petition for restoration of FM's old 42-50 MHz band were held during January of 1946 but the FCC remained steadfast and ordered that all FM broadcasters would have to change over to the new frequency range by January 1, 1947. The FCC's ruling even became a Congressional issue. House Representative William Lemke even introduced a resolution during 1947 condemning FM's frequency change and calling for a return to FM's old band, but Lemke's efforts were unsuccessful.[31] Still, with the inevitable acceptance of FM's move, the industry began preparing for the band change. Articles and advertisements for FM converters soon began appearing such as in the May 1946 issue of *Broadcast Engineers' Journal*, which introduced a converter from the Hallicrafters Company designed to allow pre-World War II FM receivers, built for FM's old frequency range, to tune in FM stations in FM's new frequency range.[32]

Armstrong's role in Capitol Hill's attempts to move FM back to its old band were acknowledged in a confidential 1948 FCC staff report prepared by staff member William Golub for the Committee on Independent Regulatory Commissions. The report mentioned that a series of resolutions had been introduced during the two previous sessions of Congress calling for the licensing of FM stations in the 42-50 MHZ band. Furthermore, the report stated that "these resolutions were inspired by Major Armstrong, the father of FM, who has asserted that the Commission's reallocation of those frequencies in 1945 and its treatment of FM generally represented a sell-out to the Radio Corporation of America."[33] Many believed that RCA had always been opposed to FM, such as DeMars who spoke of RCA's antagonistic attitude towards FM during his testimony in the Armstrong vs. Hansell case.[34] Indeed, RCA (which was a lifelong adversary of sorts of Armstrong) did not even build commercial receivers until 1946. Thus RCA had little to lose by the FCC's adoption of new FM frequency ranges. Also, RCA had made great investments in both AM radio and television, each a business enemy of FM. The question of the FCC's motives regarding their determination to move FM was partly answered when the new frequency allocations were released. FM's old frequency range was assigned to television whose frequency ranges now surround FM. Six channels were allocated to television on a shared basis in ranges of 44-50 MHz, 54-72 MHz, and 76-88 MHz, and seven channels were created between the upper end of FM and 216 MHz. It seems that the FCC was more concerned with the well-being of television than radio, especially FM radio, whose original commercial frequency band happened to stand in the way of possible television channel frequencies. This disregard for radio was made clear in Golub's FCC Staff Report, under a subsection ironically titled "Encouragement of Use of Radio." He cited the FCC's neglect of radio when he wrote that the Commission had done little more to promote the better use of radio than to provide space in the radio spectrum and to grant licenses when applications were filed. Golub also mentioned that the Federal Radio Education Committee, created in 1935 to foster the use of radio for educational purposes, had been inactive for a number of years. Finally, Golub mentioned the FCC's favoritism towards television when he wrote: "TV is an example of a service which the Commission has been particularly eager to have developed. Members of the Commission, particularly the Chairman, have recently been called upon with some frequency to deliver speeches and write articles on TV and its potentialities."[35]

When the FCC decided in September of 1947 to eliminate television's channel number one thus freeing the 44-55 MHz range for other services, Armstrong mustered a final attempt to re-secure the bandwidth for FM radio. in a brief presented before the Commission at the relocations hearing in November of 1947, Armstrong implored that the frequency range in question be restored to FM, and scolded the FCC for the harm it had caused. Armstrong began his brief by noting the transient nature of Commission personnel, and suggesting that no one in the current Commission even had first hand knowledge of the FCC's actions that had "affected, and in many instances, retarded FM development."[36] The father of FM cited two causes of judgment errors on FM's development.

The first source of misinformation came in the form of incorrect engineering advice given to the FCC by its Engineering Division, as has been discussed here. The second source of retardation came from the radio industry, particularly the AM radio industry. To back-up this charge, Armstrong recalled the January 1946 hearing based on the Zenith Radio Corporation petition to return the 42-50 MHz band to FM. At the hearing, a number of radio manufacturing companies opposed the reallocation of the band back to FM, saying that they had already prepared for the use of 88-106 MHz band, that reallocation would cause great production delays, and that substantial business losses would follow. One manufacturer stated that reallocation would cause his company to lose 75 million dollars worth of business. The deception of these manufacturers' statements became clear when Armstrong mentioned that manufacturers' subsequent post-hearing actions which contradicted their testimony from the hearings:

> "The Commission is aware that both those manufacturers, instead of making the FM sets they testified they were ready to make,

> proceeded to dump large quantities of obsolete AM equipment on the public. One of the companies did practically nothing in the way of FM production for a year. A representative of the other company testified 6 months later that it was not in production on FM receivers and his testimony made clear that he knew of no plans for going into production." [37]

Still the FCC would not grant Armstrong's request. Instead of giving the band back to FM, as of June 14, 1948, the 44-50 MHz frequency range was given to non-government fixed and mobile services such as police, fire ,transit, utility and special emergency services.

Both television and fixed/mobile radio services were at least as sensitive to interference as FM, television using FM for audio, and the fixed and mobile radio services operating in an environment less tolerant of interference than FM. Armstrong pursued this line of reasoning in his November 1947 reallocation brief. He testified that emergency services would have to be able to operate on extremely weak signals, and that interference inconsequential in broadcasting could not be tolerated in emergency services where "even a small delay might render them useless and have the most serious consequences." [38]

Curiously, the FCC now seemed to give much less credence to its own interference studies which had supposedly been the basis for FM's move to a higher bandwidth. In his confidential 1948 FCC staff report, writing on the 1945 allocation plan, Golub mentions that the plan disregarded tropospheric interference in that it neglected safety factors previously provided for tropospheric interference:

> In other words, where the staff had felt that a spacing of 200 miles was needed to avoid objectionable tropospheric interference...the plan adopted by the Commission, based on a spacing of about 150 miles between co-channel stations, probably did not provide for that protection...What happened to troposphere between September and November 1945 has not been readily ascertainable. One thing does seem to be reasonably clear -- the engineering staff was not too strong in its handling of the problem.[39]

The FCC also came to de-emphasize F2-layer transmissions during peak solar activity. In the FCC's Sixteenth Annual Report, some dozen years after the Commission's inauguration of sunspot cycle recordings, a conclusion still had not been reached as to the effects of peak solar activity. Instead of reaching a conclusion after an 11 year solar cycle, as had been anticipated, the FCC study now purported to require 22 years to complete. The Commission had decided that since "the spots of succeeding cycles are of opposite magnetic polarity...a 22-year period is involved for definite testing of these effects."[40] Thus, after FM's move to higher frequencies, the question of ionospheric interference never again seriously entered into the Commission's policy-making process.

Armstrong was a strong man but he had invested a great deal of his life fighting for the survival and success of FM. On July 22, 1948, Armstrong filed a federal suit against a number of companies, chief among them RCA, for the infringement of five of Armstrong's FM patents as well as the violation of anti-trust laws. As in his dispute with the FCC over frequency allocation, Armstrong found himself a grain of righteousness among a mountain of bureaucracy. The suit dragged on for over five years when Armstrong took his own life in January of 1954. In fact, the suit was not concluded in Armstrong's favor until some thirteen years after the inventor's death, in October 1967.[41]

Still, Armstrong's creations preserved his legacy. The period immediately after FM's assignment to the 88-106 MHz band saw initial growth. On-air FM stations increased from 46 as of June 30, 1945, to a high of 737 operating FM stations as of June 30, 1949 (see Table #1 for more detailed statistics concerning FM activity during the period immediately following the Second World War).[42] The 1950's saw a decline in the number of FM stations in operation but a number of factors helped fuel a second wave of growth in the early 1960's. One such factor was the advent of the stereo record. FM was the perfect medium for playing the high fidelity recordings. Another factor was the FCC's 1961 authorization permitting FM stations to market "background music" services, of which Muzak is a popular example, to businesses such as supermarkets, restaurants, banks, etc. An additional growth factor was the 1965 FCC ruling which forced all FM stations in markets broadcasting to over one-hundred thousand listeners to offer original programming rather than AM simulcasts, during at least half of the broadcasting schedule. This served to create a number of unique outlets on FM stations for programming unavailable on any other broadcast medium. As a result of these factors, the number of FM stations in operation has increased from under a thousand in 1961 to about five thousand today [43]

Although the FCC ultimately chose to ignore Armstrong's wisdom in his fight for the survival and success of FM, the father of Frequency Modulation was instrumental in the initial application and growth of FM radio. It is doubtful that FM would have survived had Armstrong not worked during the 1930's and 1940's to protect and preserve FM radio. His perseverance through the embodiment of bureaucracy allows us to enjoy high fidelity broadcasting and its benefits today.

Table # 1

FM Statistics in the Immediate Post-War Era

Fiscal Year Ended (As of June 30)	No. of FM Stations Operating	No. of FM Stations Authorized	No. of FM Receivers Estimated
1945	46	55	400,000
1946	63	456	500,000
1947	238	918	680,000
1948	587	1,020	2,000,000
1949	737	865	3,500,000
1950	691	732	5,500,000

Sources for Table #1 Data

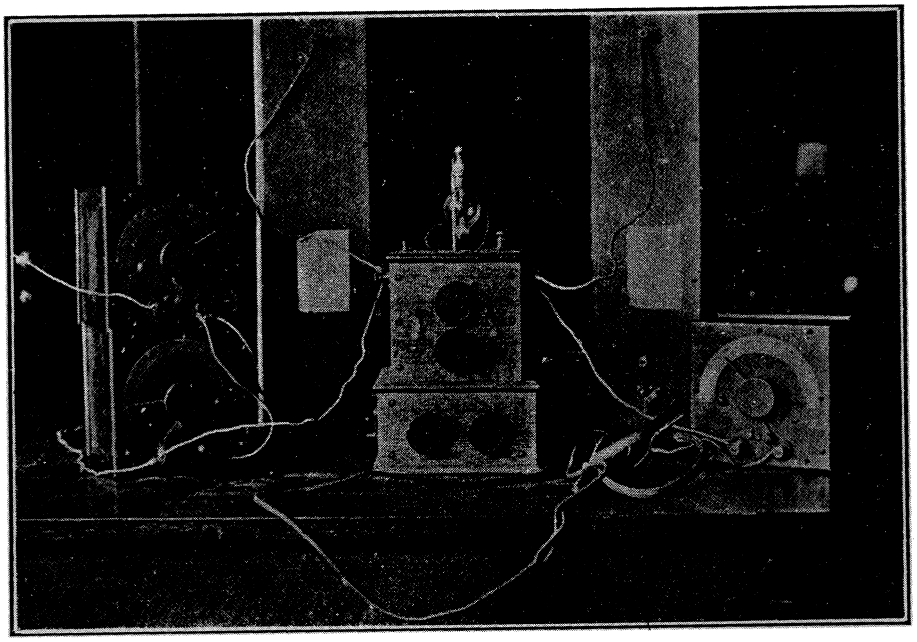
1) FCC, *Eleventh Annual Report,* (1945) pp. 19-25
2) FCC, *Twelfth Annual Report,* (1946) pp. 16-20
3) FCC, *Thirteenth Annual Report,* (1947) pp. 20-21
4) FCC, *Fourteenth Annual Report,* (1948) pp. 35-37
5) FCC, *Fifteenth Annual Report,* (1949) pp. 39-40
6) FCC, *Sixteenth Annual Report,* (1950) pp. 109-110

NOTES

1) Murray Edelman, *The Licensing of Radio Services in The United States, 1927 - 1947: A Study in Administrative Formulation of Policy* (Urbana, 1950) pp. 5-7
2) "G.E. Premiers FM" *FM* (January 1941) p.9
3) Don V. Erickson, *Armstrong's Fight for FM Broadcasting* (University, Alabama, 1973) p. 56
4) Federal Communications Commission, *Second Annual Report* (Washington, 1936) pp. 33-35
5) Paul DeMars, "Discussion of the Secret FM Hearing," *FM & Television* (November 1945) p. 47
6) "FM: A Revolution in Broadcasting?" *Electronics* (January 1940) pp. 10-11
7) Erickson, *Armstrong's Fight for FM Broadcasting*, p. 68
8) Erickson, ibid. p.68
9) Federal Communications Commission, *Sixth Annual Report* (Washington, 1940) p. 66
10) Erickson, *Armstrong's Fight for FM Broadcasting*, p. 75
11) Lawrence Lessing, *Man of High Fidelity* (New York, 1956) p. 250
12) Edwin H. Armstrong, "Discussion of Postwar Broadcasting," *FM & Television* (October 1944) p. 22

13) Edwin H. Armstrong, ibid. pp. 23 - 24
14) Edwin H. Armstrong, ibid. p. 25
15) "A Report on the FCC Frequency Allocation Hearing," *Electronics* (December 1944) pp. 92-93
16) "Radio Progress During 1944," *Proceedings of the Institute of Radio Engineers* (March 1945) p. 145
17) "RTPB on FM," *Electronics* (January 1940) pp. 10-11
18) Erickson, *Armstrong's Fight for FM Broadcasting* p. 75
19) "A Report on the FCC Frequency Allocation Hearing," *Electronics* (December 1944) pp. 92-95
20) Lessing *Man of High Fidelity*, p 258
21) Edwin H. Armstrong, "Discussion of Proposed FM Frequencies," *FM & Television* (March 1945) p. 32
22) Edwin H. Armstrong, ibid. p. 32
23) Edwin H. Armstrong, ibid. pp. 27-28
24) Edwin H. Armstrong, ibid. p. 29
25) Paul DeMars, "Discussion of the Secret FM Hearing," *FM & Television* (November 1945) pp. 48-54
26) Edwin H. Armstrong, "Discussion of Proposed FM Frequencies," *FM & Television* (March 1945) p. 29
27) Dr. Harold H. Beverage, the second awardee of The Radio Club of America's Armstrong Medal in 1938, is still living and was featured in the November 1989 issue of *The Proceedings of The Radio Club of America.*
28) Paul DeMars, "Discussion of the Secret FM Hearing," *FM & Television* (November 1945) p. 56
29) Paul DeMars, ibid. p. 47
30) Federal Communications Commission, *Eleventh Annual report* (Washington, 1945) pp. 20-21
31) Edelman, *The Licensing of Radio Services in the United States, 1927 - 1947* (Urbana, 1950) p. 27
32) Ed Stolzenberg, "Frequency Converter for the New FM Band," *Broadcast Engineers' Journal* (May 1946)
33) William W. Golub, *Staff Report on the Federal Communications Commission* (Washington, 1948) p. 42
34) Robert MacLauren, *Invention & Innovation in the Radio Industry* (New York, 1949) p. 230
35) William W. Golub, *Staff Report on the Federal Communications Commission*, pp. 59-60
36) Edwin H. Armstrong, "44 to 50 Mc. for FM Broadcast Development," *FM & Television* (November 1947) pp. 21 -22
37) Edwin H. Armstrong, ibid. pp. 21-22
38) Edwin H. Armstrong, ibid. p. 21
39) William W.Golub, *Staff Report on the Federal Communications Commission*, Appendix A-II(D), pp. 8-10
40) Federal Communications Commission, *Sixteenth Annual Report* (Washington, 1950) pp. 152-153
41 Dr. Thomas S.W. Lewis, "Radio Revolutionary," *American Heritage of Invention & Technology* (Fall 1985) pp. 40-41
42) Federal Communications Commission, *Fifteenth Annual Report* (Washington, 1949) p. 39
43 Dr. Thomas S.W. Lewis, "Radio Revolutionary," *American Heritage of Invention & Technology* (Fall 1985) p. 41

Ben Vickery is a 21 year old Senior majoring in Mechanical Engineering at the Georgia Institute of Technology, who plans to acquire a Bachelor of Science degree from the school's new Department of History, Technology, and Society. He plans to attend graduate school. This essay was adjudged to be amongst the best submitted in the contest amongst undergraduate and graduate students writing on the life and achievements of Major Edwin Howard Armstrong, under the aegis of the Grants-in-Aid Committee of The Radio Club of America.



Original apparatus with which E. H. Armstrong discovered the regenerative circuit in 1912.

THE REGENERATIVE CIRCUIT

THE REGENERATIVE CIRCUIT...Edwin H. Armstrong, *Electrical Journal,*
Vol. XVIII, No. 4, April 1921

SOME RECENT DEVELOPMENTS IN THE AUDION RECEIVERS...
Edwin H. Armstrong, *Proc. Institute of Radio Engineers,*
Vol. 3, No. 3, pp. 215 - 248, September 1915

DISCLOSURE OF THE REGENERATIVE RECEIVER...Edwin H. Armstrong

THE REGENERATIVE CIRCUIT

by **Edwin H. Armstrong**

Originally published in *THE ELECTRIC JOURNAL*, Vol. XVIII, No. 4, April 1921

EDWIN H. ARMSTRONG'S contribution to the radio art, particularly the vacuum tube radio art, is epoch making. No one who has employed his feedback or regenerative circuit can fail to appreciate its eminent value and inexhaustible possibilities. Armstrong made his invention while he was about 21 years of age and before he graduated in the Department of Electrical Engineering at Columbia University in 1913. Although the original discovery was more or less accidental, Armstrong soon appreciated the real meaning of it and applied it to the construction of the vacuum tube oscillator, which is more easily and accurately controllable than any other oscillator in existence. The regenerative receiver and the regenerative oscillator will always figure among the classical inventions and will occupy a foremost position in the research laboratory, as well as in the commercial wireless service. It entitles Armstrong to a very high place among electrical inventors.

When I was in Paris in the Spring of 1919 I met General Ferrie, the Chief of the Signal Corps of the Allied Armies. Armstrong was working under him. The general paid me several well meant compliments which I refused to accept on the ground that I had done so little for the Signal Corps.. "Ah, Monsieur le Professeur" exclaimed he, "but have you not given us Armstrong?"

PROF. M. I. PUPIN

The question as to how the invention of the regenerative or feed back circuit came about can best be answered by the statement that it was the result of a streak of luck that comes once in a lifetime. For, all things considered, the operation of the regenerative circuit involves too many new phenomena, inextricably woven together with the operation of the audion, a device whose action was clouded in the mystery of the DeForest gas ionization theory at the time the invention was made, for any one seriously to claim to a mental preconception of the operation of the feedback method of amplification and oscillation.

The invention was the result of an idea -- the kind of idea which may best be expressed in the form "what would happen if" certain additions should be made to existing apparatus. The resulting trial of these additions uncovered a series of new phenomena based on a new principle. The discovery came out of a desire to find out exactly how the audion detector detected -- not an easy thing to do in the dark ages of '11 and '12 when the very scanty literature on the subject explained (without explaining) that the action was due to ionized gas, and the audion was known to the art simply as a detector of high frequency oscillations.

To find out exactly what went on in the tube, I started an investigation. This was carried on under considerable difficulty, since my main object in life just then was supposed to be the obtaining of the degree of Electrical Engineer at Columbia University, and the professors could not be relied upon for the necessary charity mark of 6 unless a certain so-called reasonable amount of time was devoted to their particular courses.

However, during this investigation it was observed that a condenser placed across the telephone receivers in a simple audion receiver sometimes gave an increase in signal strength; not much of an increase, but nevertheless a very definite increase, and with only a small value of capacity. Now I tried a condenser across the phones many times before (what amateur has not, when graduating to the audion from crystal detector stage, where telephone shunt condensers originated) but never before had there been any observable change in signal strength.

The small condenser indicated strongly the presence of high-frequency oscillations in the plate circuit, and I thought about it a great deal without being able to account for their presence there in any satisfactory manner. During the summer vacation that year, an idea suggested by the fundamental axiom of radio, "wherever there are high frequency oscillations, tune the circuit," and the idea to see what would happen if the plate circuit of an audion detector should be tuned by means of an inductance.

All the old timers remember *CC*, later known as *MCC* and *WCC*, the Marconi press station at Wellfleet, Mass. This station was the one-hundred percent reliable testing standby of all experimenters, and on *MCC* the first tests were made. A standard audion detector system was set up and tuned in, and a tuning inductance introduced into the plate circuit of the audion. Then various things began to happen. As the plate inductance was increased, the signals were boosted in strength to an intensity unbelievable for those days, the more inductance the louder the signal, until suddenly the characteristic tone of *M.C.C.* -- the tone which any of the old timers, if they heard it on Judgment Morn, would recognize instantly -- disappeared, and in its place was a loud hissing tone, undeniably the same station, but recognizable only by the characteristic swing and the messages transmitted. A slight reduction of the plate inductance and the old tone was back again, -- and then the placing of the hand *near* a tuning condenser and the hissing tone reappeared. It required no particular mental effort to realize that here was a fundamentally new phenomenon, as obscure as the principle of the operation of the audion itself, but which opened up an entirely new field of practical operation.

Here the element of luck ended and it became simply a case of hard work, digging out the meaning of the various phenomena. A long series of experiments was carried out on different wave lengths and with various circuit modifications, and it became possible on a very small amateur antenna to receive reliable signals from the navy shore stations on the Pacific coast, the Manaos and Porto Vehlo stations in Brazil and the Marconi transatlantic station at Clifden, Ireland, with regularity every night, a performance which a few months before was undreamed of. But while the method of producing these results was known, many of the phenomena involved were as obscure as ever. The most striking of the various phenomena was, of course, the change of tone and the investigation centered on this. A number of things contributed to the suspicion that the hissing was due to the production of local oscillations by the system. With this idea and the aid of some instruments borrowed from one of the university laboratories, it was a relatively simple matter to determine that this was actually the case. Once it was apparent that the system was capable of generating oscillations, the explanation of another phenomenon became plain. I had observed on a number of occasions during the course of listening to various stations, that a whistling note would frequently appear in the telephones, which could be varied by the adjustment of the receiving apparatus. I observed this particularly in the course of listening to a wireless telephone station. After the discovery of the generating feature of the system, the explanation of the change in tone became apparent -- the system was acting as a heterodyne receiver. A series of tests confirmed this explanation.

That is briefly the story of how the invention of the feedback circuit came about, and how its properties of acting as a generator and a self-heterodyne were discovered. Since that time a vast amount of work has been carried out in investigating in detail the precise manner in which the various phenomena occur and in determining quantitatively the amplification given by the circuit in both the non-oscillating and oscillating state.

Without considering the actual mechanism of the operation of the system let us consider the physical results accomplished in practice. Consider first the results in the non-oscillating state. Measurements of the signal energy in the telephone receivers show that an amplification of from 100 to 1000 results from the regenerative action, the value depending on the strength of the incoming signals, the greater amplification being obtained on the weaker signals. By reason of the nature of the amplification, which is of the negative resistance type, the selectivity of the system is greatly increased, the gain in selectivity becoming more pronounced the lower the damping of the incoming wave. Three distinct operations are therefore carried on simultaneously in the non-oscillating state: *1*- the high frequency currents are regeneratively amplified; *2*- the selectivity of the system is increased; *3*- the amplified high-frequency currents are rectified and converted into currents of telephonic frequency.

When the amplification is increased beyond a certain limit the system passes into the oscillating state and generates, in radio circuits, high-frequency currents. In this state it is applicable to the uses of any generator, and because of its simplicity and reliability, it is particularly applicable to the heterodyne receiving system. By far the most interesting application is that of the "self-heterodyne" in which the same circuit and tube perform simultaneously the functions of generator of the local frequency, amplifier of the incoming high frequency and rectifier of the beat current to produce currents of audible frequency in the telephones; at the same time giving the increase in selectivity inherent in regenerative amplification. All these operations go on simultaneously in the same system with a single tube and out of it all comes a signal 5000 times as strong as the signal given by a simple audion circuit with a chopper, and far less subject to the disturbing influence of static and interfering signals.

On account of the very fortunate combination of sensitiveness and simplicity, its effect on the art was immediate. The amplifying feature made possible transoceanic signaling. The self-heterodyne feature contributed very largely to the change from spark to continuous wave systems. The generating feature has been responsible for the development of carrier wave or wired wireless signaling. And this progress can be attributed, not to any carefully preconceived ideas, but to the versatile properties of the regenerative circuit and the luck that led to its discovery.

SOME RECENT DEVELOPMENTS IN THE AUDION RECEIVER

By **Edwin H.Armstrong**

Presented before the Institute of Radio Engineers, New York, March 3, 1915, and The Boston Section, April 29, 1915
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THE AUDION AS DETECTOR AND AMPLIFIER

The fundamental operating characteristic of the audion is the relation between the wing current and the potential of the filament. Such a characteristic is shown in Figure 1, and from it we see that a positive charge placed on the grid produces an increase in the wing current, and that a negative charge placed on the grid produces a decrease in the wing current.

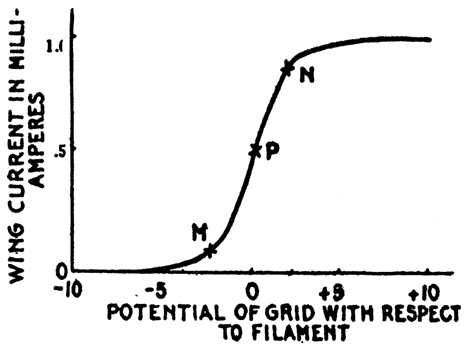

FIGURE 1

When the audion is used as an amplifier, and an alternating e.m.f. is impressed between the grid and the filament, the continuous current of the wing circuit will be varied in accordance with the characteristic of Figure 1, producing on the continuous current a superimposed a.c. wave in phase with and of the same frequency as the impressed e.m.f. Diagrammatically this action is shown in Figure 2.

The action of the audion as a detector of radio frequency oscillations is very different from its action as a simple amplifier. Some form of connection must be used, such that the effect of a group of radio frequency oscillations in the grid circuit of the audion is translated into a single audio frequency variation of the current in the telephones.

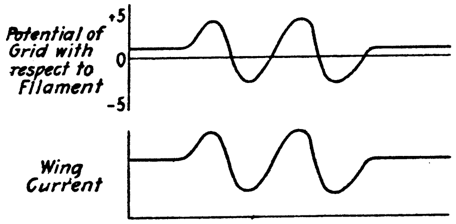

FIGURE 2

The usual method is to make use of the valve action between the hot and cold electrodes at low pressures, and the connection used to do this is shown in Figure 3.

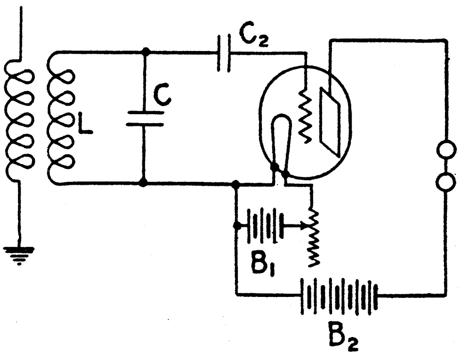

FIGURE 3

In this method of connection there are two distinct actions; one rectifying and the other amplifying. The closed oscillation circuit: LC, filament, grid, and condenser C$_2$, behaves exactly as a Fleming valve receiver, the incoming oscillations being rectified between the grid and filament and the rectified current being used to charge the condenser C$_2$, (the side connected to the grid being of course negative). The negatively charged grid then exerts a relay action on the wing current, decreasing it; the wing current returning to its normal value as the charge in the grid condenser leaks off by way of the grid and the grid assumes its normal potential. If the audion is properly constructed, the relay action results in an amplification of the energy available for use in the telephones over that which would be available in a simple rectifier. Figure 4 indicates the features of the valve method of detection.

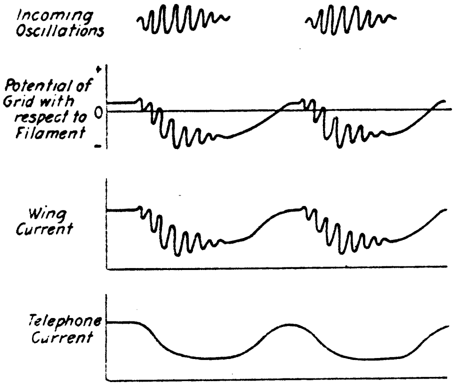

FIGURE 4

Working in conjunction with Professor Morecroft, I have recently secured oscillograms which confirm explanations already advanced and these oscillograms and the means by which they were obtained are herewith shown in Figures 5, 6, and 7.

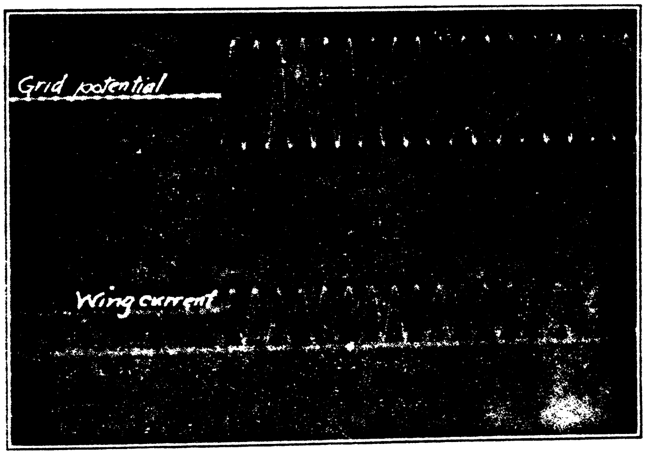

FIGURE 5

It will be seen, therefore, that using the audion as a detector of radio frequency oscillations, it has been shown that it addition to operating as a rectifier it simultaneously acts as a repeater of the radio frequencies; so that oscillations in the grid circuit set up oscillations of similar character in the wing circuit of the audion.

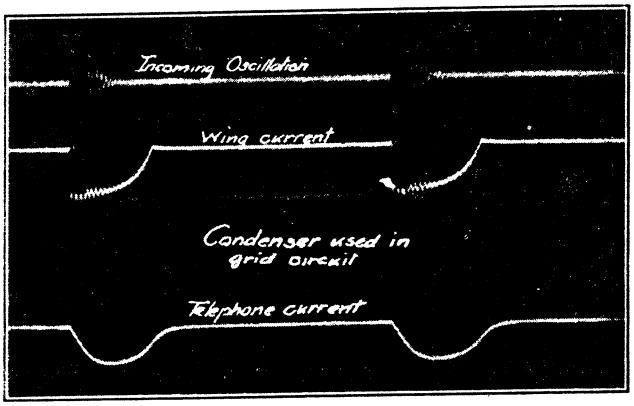

FIGURE 6

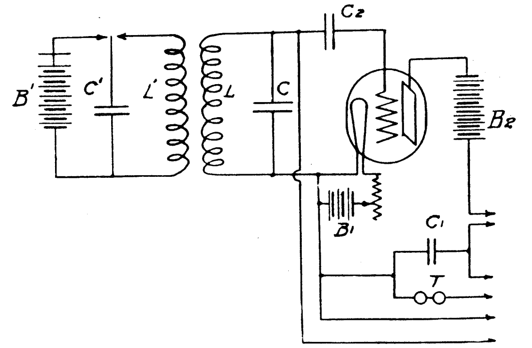

FIGURE 7

In the ordinary detector system no use is made of the repeating action, and it is the purpose of the present paper to show that it may be turned to account to produce improvements in the reception of signals which completely overshadow any of the particular advantages of the audion when used as a simple detector. The ordinary detector circuit is illustrated by Figure 3 and the phenomena present therein may be summed up diagrammatically by the curves of Figure 4. It will be seen from these that the radio frequency oscillations present in the wing circuit of Figure 3 with the ordinary audion are necessarily small and also that they are of no value in producing a response in the telephones; but by providing means for increasing their amplitude and means for utilizing them to reinforce the oscillations of the grid circuit, it becomes possible to produce some very remarkable results.

REINFORCEMENT OF RADIO FREQUENCY OSCILLATIONS BY THE AUDION

There are two ways of reinforcing the oscillations of the grid circuit by means of those two circuits together in the manner shown in Figure 8.

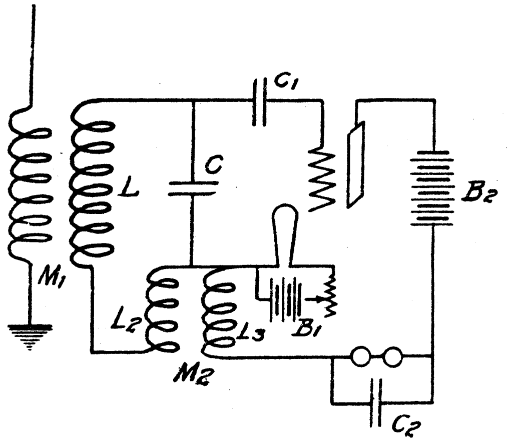

FIGURE 8

This is essentially the same as Figure 3, but modified by the introduction of the inductively-coupled coils L_2 and L_3 in the grid and wing circuits respectively and by the condenser C_2 which forms a path of low impedance across the telephones for the radio frequencies. In such a system, incoming signals set up oscillations in the grid circuit which repeat into the wing circuit producing variations in the continuous current, the energy of which is supplied by the battery B_2.

By means of the coupling M_2, some of this energy of the wing oscillations is transferred back to the grid circuit, and the amplitude of the grid oscillations thereby increased. The amplified grid oscillations then react on the wing circuit by means of the grid to produce larger variations in the wing current, thus still further reinforcing the oscillations of the system.

Simultaneously with this procedure, the regular detecting action goes on; the condenser C_1 is charged in the usual way, but accumulates a charge which is proportional, not to the original signal strength but to the final amplitude of the oscillations in the grid circuit. The result is an increased response in the telephone proportional to the energy amplification of the original oscillations in the grid circuit. It will be observed from the operating characteristic (the relation between the grid potential and the wing current), that the amplitude of the variation in the wing current is directly dependent on the variation of the grid potential.

This indicates that the grid circuit should be made up of large inductance and small capacity to obtain the maximum voltage which it is possible to impress on the grid. For moderate wavelengths the tuning condenser C of the grid circuit may be omitted altogether and the capacity of the audion alone used to tune the circuit. For long wavelengths, the distributed capacity of the grid circuit inductance becomes so high with respect to the capacity of the audion that better results are obtained by the use of a tuning condenser to fix definitely the points of maximum potential difference across the grid and filament of the audion.

In the second method of reinforcing the oscillations of the grid circuit the wing circuit of the audion is tuned by means of an inductance introduced as shown in Figure 9.

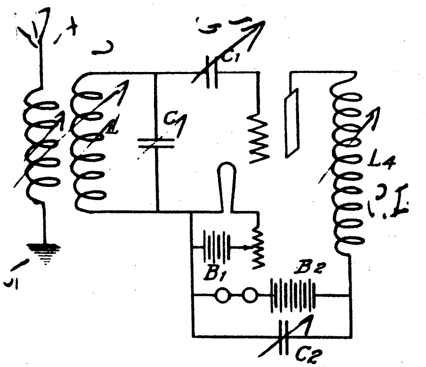

FIGURE 9 3.C.

This differs from the ordinary detector circuit of Figure 3 by the addition of the coil L_4 and the condenser C_2. The manner in which the grid oscillations are amplified may best be understood by the following analysis. With no oscillations in the system, the potential difference between filament and wing will be approximately the voltage of the battery B_2, but when oscillations are set up in the grid circuit, causing radio frequency variations of the wing current, the potential of the wing with respect to the filament varies as the reactance voltage of the wing inductance alternately adds to and subtracts from the voltage of the battery.When a negative capacity charge is placed on the grid, the wing current will be reduced and the direction of the reactance voltage of the wing inductance will therefore be the same as the voltage of the battery B_2.

The reactance voltage will therefore add to the battery voltage and the difference of the potential between wing and filament and also between wing and grid will be increased. Similarly when a positive charge is placed on the grid the wing current is increased and the reactance voltage of the wing inductance opposes the battery voltage, producing a decrease in the potential difference between grid and wing. Hence, supposing a negative capacity charge is placed on the grid, the tendency of the corresponding increase in the potential of the wing with respect to the grid will be to draw more electrons out on the grid, thereby increasing the charge in the condenser formed by the wing and grid, the energy for supplying this charge being drawn from the wing inductance as the wing current decreases. The increased negative charge on the grid tends to produce a still further decrease in the wing current and a further discharge of energy from the wing inductance into the grid circuit. On the other hand, when a positive charge is placed on the grid, the potential difference between grid and wing is reduced and some of the energy stored in the capacity formed by them is given back to the wing inductance. During this part of the cycle, electrons are being drawn into the grid from the surrounding space to charge the grid condenser in accordance with the well known valve action, and this, in effect, is a conduction current, so that a withdrawal of energy, however, a well defined resonance phenomena between the audion capacity and the wing inductance is to be expected and in the reception of signals such is found to be the case. When the wing inductance is properly adjusted at the resonance frequency, energy from the wing circuit is transferred freely to the grid circuit and oscillations build up therein and are rectified in the usual way.

A curve showing the general relation between signal strength and value of wing inductance is shown in Figure 10, the circuits used being those of Figure 9.

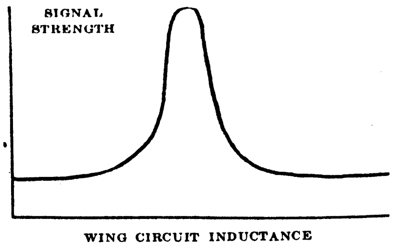

FIGURE 10

As the capacity of the audion is the main means of transferring energy from the wing to the grid circuit, best results are obtained when the condenser C is very small. On account of the very small capacity of the audion, the effectiveness of this method of tuning is more pronounced at the higher frequencies, but by the use of a shunt condenser across the inductance of the wing circuit very good amplification is secured on frequencies as low as 30,000 cycles (10,000 meters wavelength.) The best results, however, are obtained with some combination of coupling and wing circuit tuning, as illustrated in Figure 11.

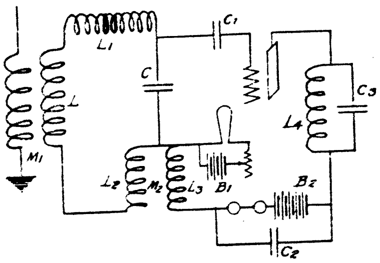

FIGURE 11

Other methods of coupling may be employed between the grid and wing circuits, electrostatic and direct magnetic couplings are being illustrated in Figures 12 and 13.

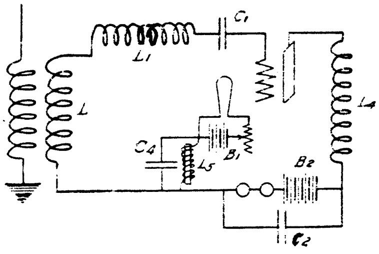

FIGURE 12

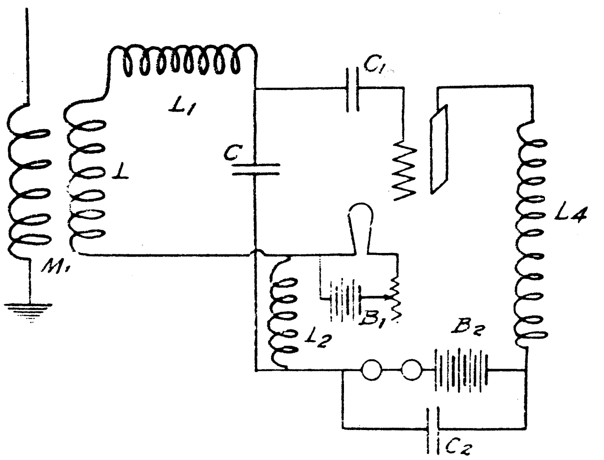

FIGURE 13

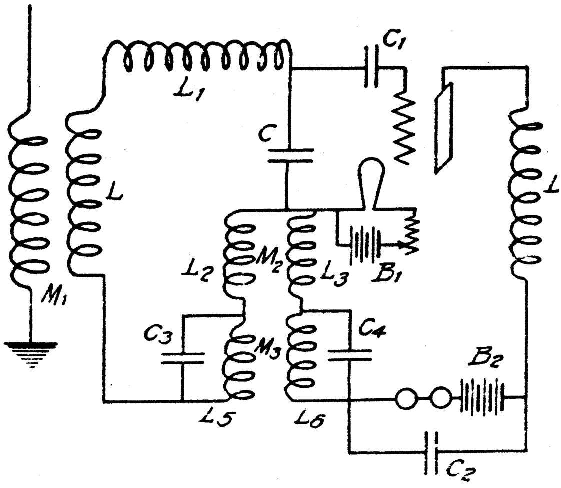

FIGURE 14

The arrangement of Figure 13 operates in the same way as the system with the two coil coupling; but the electrostatic coupling of Figure 12 works in an odd way. It is necessary, in this connection, to complete the wing circuit for the continuous current of the battery and this is done by shunting the coupling condenser C_4 by a coil of high inductance. The continuous current of the wing circuit flows thru this coil and C_4 provides a path of low impedance around this coil for the radio frequencies oscillations of both grid and wing circuits. When a positive charge is placed on the grid, an increase in the wing current results, the alternating component of the wing current charging the condenser C_4 and the sum of the currents passing thru C_4 and L_4 equaling the current thru the audion. When a negative charge is placed on the grid the current thru the audion is reduced and the inductance L_5 discharged into the condenser shunted across it, charging it in the opposite way to that caused by the increase in the wing current. In both cases, C_4 then discharges thru the grid circuit reinforcing the oscillations therein.

AUDIO FREQUENCY AMPLIFICATION

It is possible to combine with any of these systems a system of audio frequency circuits which amplify the telephone current in exactly the same manner as the radio frequency oscillations are amplified, and such a system is shown in Figure 14.

Here M_2 represents the coupling for the radio frequencies and the coils are of relatively small inductance. M_3 is the coupling for the audio frequencies, and the transformer is made up of coils having an inductance of the order of a henry or more. The condensers C_3 and C_4 have the double purpose of tuning M_3 to the audio frequency, and of by-passing the radio frequencies. The total amplification of weak signals by this combination is about 100 times, with the ordinary audion bulb. On stronger signals, the amplification becomes smaller as the limit of the audion's response is reached.

THE AUDION AS A GENERATOR AND BEAT RECEIVER

Any repeater, which is also an energy amplifier, may be used to produce continuous oscillations by transferring part of the energy in the circuit containing the battery back to the controlling circuit to keep the latter continuously excited. By providing a close enough coupling between the grid and wing circuits, sufficient energy is supplied to the grid circuit to keep it in continuous oscillation, and as a consequence thereof oscillations of similar frequency exist in all parts of the system

The frequency of these oscillations is approximately that of the closed grid circuit if the tuning condenser of that circuit is large with respect to the capacity of the audion. If this capacity is small, then the wing circuit will exert a greater influence on the frequency of the system, and it will not approach that of the grid circuit so closely. When such a system of circuits is in oscillation, it has been found possible not only to receive continuous waves by means of the beat method but also very greatly to amplify then as well.

The phenomena involved may best be understood by reference to Figures 15 and 16, which show the relation between wing current and time at the beginning of oscillation. When the audion begins generating, the grid oscillations are continuously rectified to charge the grid condenser, and this charge continuously leaks off either by way of the grid or by means of a special high resistance placed in shunt with the condenser. As the negative charge builds up in the grid condenser, it decreases the average value of the continuous current component of the wing current and therefore limits the amplitude of the oscillations of the grid circuit until a point is finally reached where the rate at which electricity is supplied to the grid condenser is just equal to the rate at which it leaks off.

Consider now the effect on the system of an incoming continuous wave having a frequency slightly different from the frequency of the local oscillations.

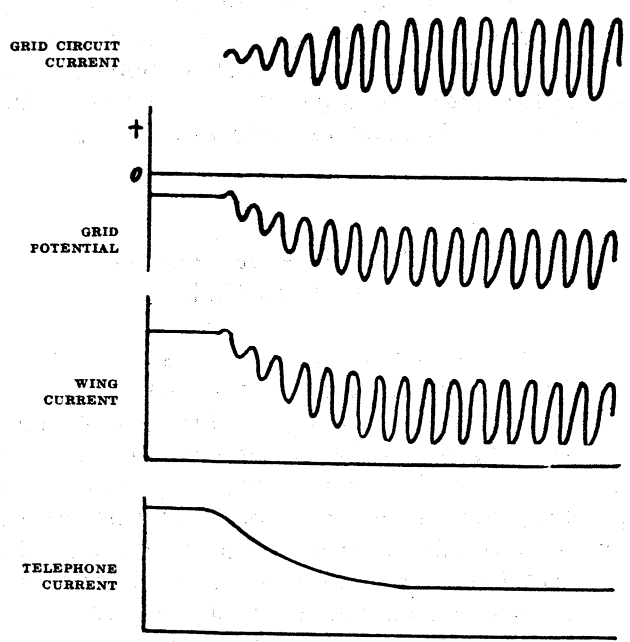

FIGURE 15

The presence of the local oscillations will not in any way interfere with amplifying powers of the system and the incoming oscillations will build up in exactly the same manner as for the non-oscillating state but to a greater degree because of the closer grid and wing coupling. Simultaneously with the amplifying of the incoming wave, beats are produced between the local and the signaling currents, the effect being alternately to increase and decrease the amplitude of the oscillations in the system.

From Figure 15 it will be apparent that when this steady state is reached an increase in the amplitude of the grid oscillations by any means whatever will increase the negative charge in the grid condenser, producing a decrease in the average value of the wing current and hence a decrease in the telephone current. On the other hand, a decrease in the amplitude of the oscillations will allow some of the negative charge in the grid condenser to leak off and thereby permit an increase in the telephone current. Hence, when incoming and local oscillations add up, the negative charge in the grid condenser is increased and a decrease in the telephone current results. When the two frequencies are opposed, some of the charge in the grid condenser leaks off and an increase in the telephone current occurs. The result is the production in the telephones of an alternating current having a frequency equal to the difference in the frequencies of the local and incoming oscillations and having the very important property of being almost simple harmonic.

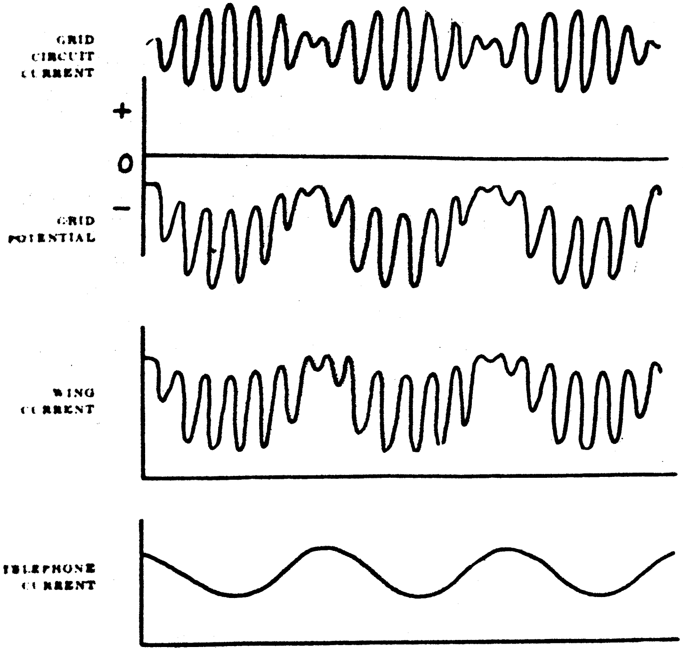

FIGURE 16

Figure 16 illustrates the characteristics of this method of reception. The complete phenomena may be summed up as follows. Incoming oscillations are simultaneously amplified and combined in the system to produce beats with a local oscillation continuously maintained by the audion. The radio frequency beats are then rectified by the audion to charge the grid and the grid condenser, and this charge varies the electron current to produce an amplifying action on the current in the telephones.

When the grid condenser is omitted, the beat phenomenon is slightly modified, and the audio frequency variation of the telephone current is produced according to the asymmetric action outlined in a previous publication dealing with the operating features of the audion. The system is more sensitive with the grid condenser, but the same general result is obtained by either method of reception.

PECULIAR FEATURES OF OSCILLATION

Some very interesting features of operation accompany the production of oscillations in the system. Suppose the audion is not oscillating, and the grid and wing coupling is fairly weak. As this coupling is increased, the point at which oscillations begin is indicated by a faint click in the telephones accompanied by a slight change in the character of the static. The oscillations produced are usually so high in frequency and constant in amplitude that they are entirely inaudible.

As the coupling is still further increased, a rough note is heard in the telephones the pitch decreasing with increase of coupling. This note is produced by the breaking up of the oscillations into groups, and it occurs whenever electricity is supplied to the grid condenser at a greater rate than that at which it can leak off. The result is that the grid is periodically charged to a negative potential sufficient to cut off entirely the wing current, causing a stoppage of the local oscillations until the grid charge leaks off and the wing current re-establishes itself.

The frequency of this interruption depends largely on the capacity of the grid condenser, the resistance of its leakage path, and the amplitude of the local oscillations; and it may be varied from several hundred down to one or less per second. This effect is sometimes troublesome in the reception of signals, especially with high vacuum tubes. It may be eliminated, however, by increasing the leak of the grid condenser by means of a high resistance shunt. The best coupling for receiving continuous waves lies somewhere between the point at which oscillations start and the point at which interruption begins, and can only be determined by trial.

In this region, trouble is sometimes experienced by the appearance of a smooth musical note in the telephones. This occurs under certain critical conditions of coupling with the antenna when the grid circuit oscillates with two degrees of freedom. Two slightly different frequencies are therefore set up, producing beats which are rectified by the audion in the usual way. This effect is quite critical, and when it causes interference with signals, a slight readjustment of the circuits will usually make it disappear. It may, however, be made perfectly steady and reproduced at will by the system shown in Figure 17, where two grid circuits of different periods are provided. Two frequencies are therefore generated one having the frequency of the circuit LCL$_2$, and the other the frequency of the circuit L'C'L$_2$C. This arrangement may replace to advantage the ordinary buzzer for producing groups of oscillations. *The foregoing explanations refer to the audion only when it is used as an electron relay.*[2] *When there is an appreciable amount of gas, in the tube in the ionized state, disturbances of an entirely different character occur.*

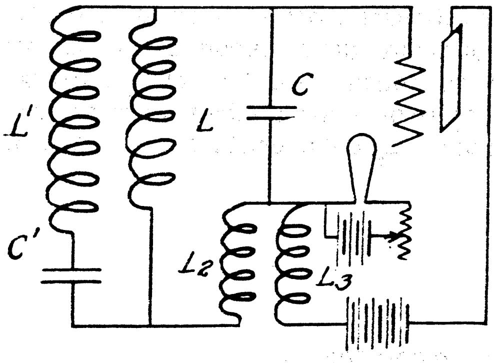

FIGURE 17

AUDIO FREQUENCY TUNING

One of the very important advantages of the receiver when used for continuous waves is that the alternating current produced in the telephones is almost a pure sine wave. Only when the audio frequency is simple harmonic can selectivity be obtained by tuning the telephone circuit. A distorted wave such as that produced by spark signals possesses many harmonics and as each may be picked out by the tuned telephone circuit there is little chance of separating two spark signals by audio frequency tuning. With continuous waves, however, the pure wave produced by the beat method of reception makes it possible to obtain selectivity by the audio frequency tuning, resonance being fully as sharp as in the radio frequency circuits. Two methods of audio frequency tuning are shown in Figures 18 and 19.

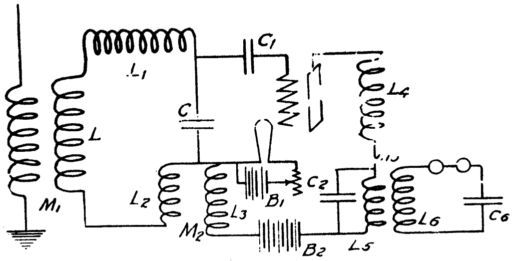

Figure 18

In Figure 18, the telephone is inductively connected to the wing circuit of the audion by means of a transformer the secondary of which includes besides the telephone a tuning condenser. In this connection, the telephone, with a resistance of many thousand ohms, is placed directly in the tuned audio frequency circuit, and hence for good tuning the inductance of the coil L$_6$ must be made extremely large to secure the necessary ratio of the reactance of L$_5$ to the resistance of the circuit.

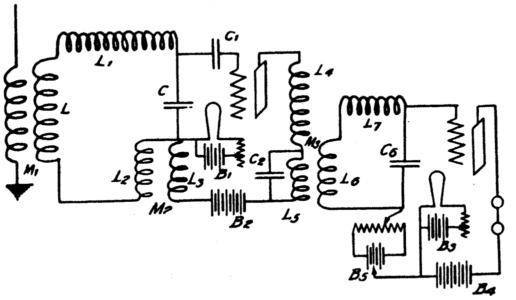

Figure 19

This disadvantage is overcome in the system of Figure 19 by removing the telephones from the audio frequency circuit, and using the latter to operate a second audion. The telephones may then be placed in the wing circuit of this audion without adding appreciably to the damping of the circuit. The tuning of the circuit L$_7$C$_6$ may therefore be made very sharp with reasonable values of inductance simply by keeping the resistance low. In this case considerable amplification is obtained by the use of resonance in the transformer M$_3$ to increase the voltage impressed on the grid of the second audion. The great advantage of this kind of tuning is shown by the following example. Suppose the incoming signal has a frequency of 50,000 cycles, and the local frequency is 49,000 cycles. The differential frequency is 1,000 and the audio frequency circuit is tuned accordingly. An interfering wave 1 per cent, shorter than the signaling wave, or 49,500 cycles, will produce an audio frequency of 500 cycles per second, which will not appear at all in the wing circuit of the second audion unless it is many times stronger than the 1,000 cycle signal.

This combination of radio and audio frequency tuning is at the present time even when the sending station is equipped with an alternator, as the slight changes in frequency of the radiated wave produce changes in the beat frequency of the receiver which carry it out of range for the sharply tuned audio frequency circuit. A disadvantage of this method of tuning is that atmospheric disturbances produce a musical note due to shock excitation of the audio frequency system. Very loose coupling with the wing circuit of the first audion is a partial remedy for this. There are times, however, when interference is more troublesome than static and in such cases the method may be used to great advantages. If desired, both radio and audio frequency tuning can be carried out in the same audion as indicated in Figure 14. This combination is apt to be somewhat troublesome to operate as a cumulative amplification is obtained in the audio frequency as well as in the radio frequency system.

CASCADE SYSTEMS

Where a greater amplification than can be obtained with one audion is required, cascade working of the radio frequency systems may be resorted to by coupling together two or more audion systems, each connected as already described, in the manner indicated in Figure 19. The incoming oscillations in the first audion system are amplified in the usual manner and set up oscillations in the second system by means of the coupling M_3 (See Figure 20). The oscillations initially set up in the second system are again amplified, and then rectified in the second audion to produce audible response in the telephones. For the reception of spark signals, considerable adjustment is required to get the best results without causing one or the other or both of the systems to generate oscillations. It will be found that after the first circuit is adjusted to the point of oscillation and the second is coupled with it, the strength of signal in the first system will be reduced owing to the withdrawal of energy from it by the second system. The signals may then be again brought up in strength by increasing the coupling between the grid and wing circuits of the first audion until the appearance of the local oscillations indicates that the limit of amplification has been reached. By careful adjustment about a thousand times amplification and very sharp tuning can be obtained with two steps.

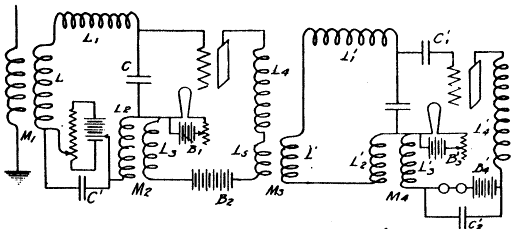

FIGURE 20

For continuous wave reception, there are several methods of operating cascade systems. It is possible to have either system generate oscillations, the other system acting simply as an amplifier or both systems may be made to generate in synchronism.

It will generally be found that when both systems produce oscillations, beats will be produced, so that a continuous note is heard in the telephones; but by adjusting the frequency of one of the systems the pitch of this note will be reduced as the two systems approach synchronism, until finally at one or two hundred beats per second the two systems pull into step in much the same way as two alternators. The ability of the two systems to keep in step depends mainly on the value of the coupling between them, and the closer this is the better the two hold together.

There is still another way of working this combination, and that is asynchronously. In this case beats are continuously produced in the system so that a continuous note is heard in the telephone, but the circuits may be so adjusted that the note is not loud enough to be troublesome or it may be tuned out of the telephone in the manner previously described. Incoming oscillations are combined in the system to produce beats with the beats already present so that a rather curious note is heard. Very good amplification is secured by this method though naturally the system is troublesome to operate.

It may be noted here that whenever a signal is too weak to read with one audion system and cascade operation becomes necessary, it is always better practice to use the cascade circuits for the radio frequencies, even if the regenerative circuits are not employed with each individual audio system. The frequency of the oscillations set up in the circuits by static are, under normal conditions, the same as those of the incoming signal; and the static is therefore never amplified more than the signal. Usually it is amplified to a somewhat lesser extent, especially if regenerative circuits are employed. In the cascade systems used for audio frequencies, a different condition exists. It is ordinary practice to connect the different stages by means of transformers, and this leads to conditions which cause the system to produce greater amplifications of the higher frequencies. The rate of change of the wing current of the detecting audion produced by static corresponds to a very high frequency, and as such is invariably amplified to a greater extent than the signal.

There is a second method of receiving continuous oscillations which makes use of the generating feature of the audion, but does not employ the beat phenomena. The amplifying ratio of the audion depends more or less directly on the value of the wing current, and by varying this current periodically there will be a corresponding periodic change in the amplifying power of the audion. Hence an audion arranged to repeat a continuous wave under such conditions will produce in its wing circuit oscillations which vary periodically in amplitude, and which may therefore be received by a simple audion system.

The first audion may be arranged to produce the necessary variation in its amplifying power in the manner indicated in Figure 21, which also shows the complete circuits for carrying out this method of reception. Here $C_1L_1L_2C_2$ is an audio frequency system designed to produce audio frequency oscillations; and P is a potentiometer for adjusting the potential of the grid so that on the negative part of the oscillation in the wing circuit, the wing current is reduced practically to zero. The radio frequency circuit $C'LCC_1$ is tuned to the oscillation frequency of the incoming wave. The radio frequency oscillations cannot be detected in the first audion system as the strong audio frequency current circulating in this system would produce a continuous note in the telephone receivers of such strength as to render inaudible all save very strong signals. By arranging to detect the oscillations in the second audion system coupled to the wing circuit of the first, interference of this sort is avoided; as the circuit L_4C_4 has a very high impedance for the audio frequency currents and the effect produced thru the magnetic coupling of L_3 and L_4 on the second system is negligible.

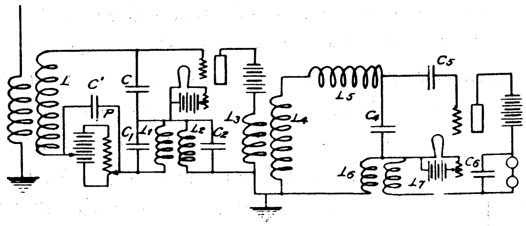

FIGURE 21

The capacity current between these two coils thru the telephones to ground is, however, appreciable; and to avoid it it is advisable to ground their two adjacent ends as shown. The action of the system may be summed up as follows. The first audion system varies the amplitude of the incoming radio frequency oscillations at an audio frequency, and the second audion system amplifies and detects the radio frequency oscillations supplied to it by the first system. Diagrammatically, the phenomena occurring are as illustrated in Figure 22.

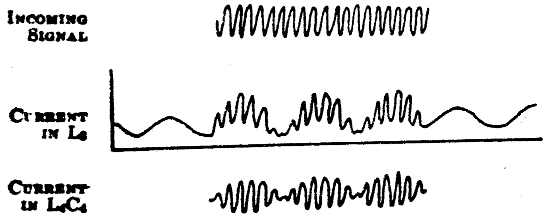

FIGURE 22

The system gives about the same response as can be obtained with a single audion working with the beat method of reception. The advantages derived from the heterodyne method of amplification and the dependence of the audio frequency note in the receivers on the wave length are, of course, lacking; but for the reception of waves having a frequency higher than that at which beat reception is practicable, this method is of value.

EFFECTS OF ATMOSPHERIC DISTURBANCES

A very interesting feature of these receiving systems is their behavior under conditions of severe atmospheric disturbances, particularly when used for receiving continuous waves. Their success under such conditions is due to the fact that they combine in addition to their inherent property of responding more readily to a sustained wave than to a strongly damped one, the characteristics of the two most effective static eliminators known; the balanced valve and the heterodyne receiver. The function of the balanced valve is a physiological one, as it simply provides a means to shield the ear from the loud crashes which temporarily impair its sensitiveness for the relatively weak signals. In effect, it puts a limit on the noise which can be produced in the telephone by a stray, regardless of its amplitude.

Now the effect of the static on an audion is to build up a negative charge on the grid, reducing the wing current, and the limit of the response which can be produced in the telephones is reached when the wing current is reduced to zero. Under ordinary conditions, this limit is too great to do much good; but when the audion is generating it is possible, by proper adjustment of the amplitude of the local oscillations, to reduce the wing current to a point just above the lower bend in the operating characteristic so that the audion is rendered insensitive to a further increase in the negative charge on the grid.

The strays which cause serious interference are of a much greater amplitude than the local frequency, so that no appreciable interaction between the two takes place, and the wing current is invariably decreased. Since the decrease in the wing current is not in proportion to the change in the grid potential, the response in the telephone and the effect on the ear of the operator are correspondingly reduced.

Static of smaller amplitude than the local oscillations may interact with them to produce either an increase or a decrease in amplitude of the oscillations in the grid circuit and may therefore cause either a decrease or an increase in the wing current. The wing current can, of course, increase to a relatively large value, but as it is impossible for the wing current to increase faster than the charge in the grid condenser can leak off, the rate of increase is necessarily slow. The response in the telephones is therefore not so disturbing as would be caused by a decrease of similar value where the rate of change of current is usually large.

When the system is operated without an auxiliary leak around the grid condenser, a peculiar paralysis of the audion is frequently caused by heavy static, no sound of any kind being heard in the telephones for a considerable length of time. If the apparatus is not touched, the paralysis may last for many minutes, and then suddenly disappear and the former sensitiveness be restored. The effect is primarily caused by the charging of the grid condenser to a sufficient potential to cut off entirely the flow of electrons to the wing, thereby decreasing the wing current to zero.

Now the way in which the negative charge in the grid condenser leaks off is chiefly by means of the positive ions in the tube, which are drawn into contact with the grid when it becomes negatively charged. These positive ions are the result of ionization by impact, and when the voltage of the wing battery is properly adjusted, they can be produced only in the region between the grid and the wing, since the velocity attained by the electrons between the filament and grid is very low.

When the grid is charged to a high negative potential, it keeps all the electrons between the grid and filament thereby barring them from the region between grid and wing. Hence the production of positive ions must cease and the usual means of removing the negative charge from the grid vanishes. The resistance of the leakage path of the grid condenser must then be almost infinite, as is shown by the very long time taken for the charge to leak from a condenser of approximately 0.0001 microfarads capacity. The effect is naturally the more pronounced the higher the vacuum, as the number of positive ions present is correspondingly reduced.

A resistance of several hundred thousand ohms placed across the grid condenser gives a leak which is independent of the value of the wing current and which effectually prevents trouble of this kind. With the very high vacua now obtainable by the use of a molecular pump, there are practically no positive ions present so that the auxiliary leak is always necessary. Under these conditions, it not only prevents paralysis by the static but it also removes from the grid condenser the excess of negative electricity which accumulates in it, thereby increasing the sensitiveness of the audion and the sharpness of the signals in the telephones. The very high potentials to which the grid condenser may be charged by the static when it is not provided with an auxiliary leak are surprising. These potentials may be measured in a very simple and accurate way, here described.

After a stray has cut off the wing current, if we continuously increase the capacity of the grid condenser the potential across it, and hence the potential of the grid, with respect to the filament, will be decreased inversely as the capacity. A point will finally be reached where the grid potential is sufficiently reduced to allow the wing current to flow. When this occurs it indicates that the potential of the grid condenser is slightly less than that shown by the operating characteristic as necessary to reduce the wing current to zero.

The potential to which the grid condenser was originally charged is equal to this voltage times the ratio of the capacity of the condenser at which the wing current began to flow to the original capacity. Voltages of over a hundred are not uncommonly reached by the grid; and as one volt represents a very strong signal, the difficulties of the static problem are very forcibly presented.

The fact that static of large amplitude produces almost invariably a decrease in the wing current while a signal (with beat reception) produces alternately an increase and decrease in the wing current is a circumstance of which it should be possible to take advantage. The circuits can be arranged to rectify the wing current in such a way that only the increases in this current are available to produce a response in the telephones, but in carrying this method out, trouble is experienced from a shifting zero.

A better way of making use of the difference in response is the following one. Suppose that we arrange two complete receiving systems oscillating in step with each other, but so related to the antenna that the beat currents in the two systems are 180 degrees apart. The result of this will be that at the instant when the incoming signal is producing an increase of current thru the telephones in one receiver, it will be producing a decrease of current thru the telephones of the other receiver; so that the two telephone currents are 180 degrees out of phase.

Static of large amplitude does not interact with the local frequencies, and will produce simultaneously in each receiver a decrease in the telephone current. These two currents are therefore in phase with each other. On replacing each telephone by the primary of a transformer, and connecting their secondaries thru a telephone in the proper phase, it is possible to balance out the static and at the same time secure an additive response of the signals from each receiver.

An arrangement of circuits by means of which this method can be carried out is shown in Figure 23.

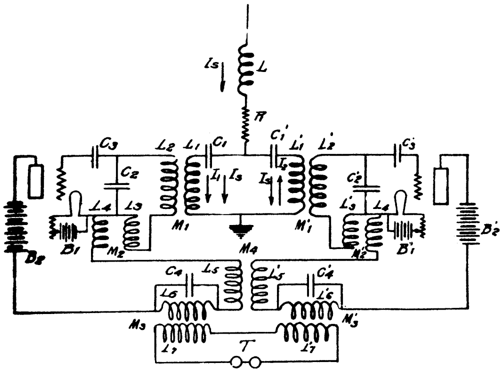

FIGURE 23

Here two oscillating receiving systems are kept in step by means of the circuits $L_1C_1C_1'L_1'$. L_1C_1 and $L_1'C_1'$ are identical, and each is tuned separately to the frequency to be received. When both audions are oscillating in step, the flow of current in these circuits as indicated by the vectors of Figure 23 will be alternately up on one side and down on the other. The point between the condenser C_1 and C_1' will be a node; and the antenna may be connected to this point without disturbing the conditions appreciably if a resistance R placed as indicated is included in the antenna. This resistance need not be large enough to interfere seriously with the signal strength; it need only be large with respect to the resistance of the circuit $L_1C_1C_1'L_1'$, which circuit has a very low resistance.

Incoming oscillations pass thru the divided circuit as indicated in the diagram, and therefore are in phase with the local oscillations of one receiver 180 degrees out of phase with the local oscillations of the other. This produces the desired result in the currents thru the transformers of the circuit T which act in the manner already described.

It is found in practice that the oscillations set up in each system by the incoming signals tend to neutralize each other thru the circuit $L_1C_1C_1'L_1'$. This effect is avoided by introducing in the wing circuits a differential coupling arranged to neutralize the coupling between the two grid circuits. It is possible to do this, as it does not affect the coupling of either receiver with the antenna, and does not interfere with the local operation until the effective coupling between the two systems is reduced to a point below which they will no longer remain in step. There are other ways of securing the same result, but the system shown will illustrate the general procedure in carrying out this method of balancing.

The practical results obtainable with these receivers may perhaps be of interest. At the present time, signals from all high power stations from Eilvese (Germany) to Honolulu are heard day and night at Columbia University with a single audion receiver. Cascade systems give correspondingly better results, two stages being sufficient to make the night signals of Honolulu audible thruout the operating room. Interference with the signals from Nauen by the arc station at Newcastle, New Brunswick (Canada), is very easily eliminated by means of an audio frequency tuning circuit; and this is the most severe interference we have yet experienced, the two frequencies sometimes differing by less than 1 per cent, and the arc signals being much the stronger.

These receivers have been developed in the Research Laboratory of Electo-Mechanics, Columbia University; and are mainly the result of a proper understanding and interpretation of the key to the action of the audion; the grid potential-wing current curve. In conclusion, I want to point out that none of the methods of producing amplification or oscillation depend on a critical gas action; they depend solely on the relay action of the tube employed (electron or gas relay) and the proper arrangement of its controlling circuits.

SUMMARY: The action of the audion as a detector and simple amplifier is explained, with the method of verification of the theory by means of oscillograms. To reinforce the oscillations in the grid circuit two methods are employed: first, to couple the grid circuit to the wing circuit and arrange the latter to permit radio frequency currents to pass freely in it; and second, to use a large inductance in the wing circuit, thereby tuning it to the incoming frequency (in conjunction with the capacity between the filament and wing in the audion itself). Both methods may be used together. Various methods of coupling grid and wing circuits are shown. Methods of combined audio and radio frequency amplification are described.

The audion, being a generator of alternating current of any desired frequency, can be used as a beat receiver. A steady audion generator of regular groups of radio frequency oscillations is illustrated. Various methods of audio frequency tuning permitting high selectivity are possible. By the use of two audions in cascade, amplifications as high as 1,000 are attainable. The cascade systems can be arranged so as to operate both audions either synchronously or non-synchronously.

As an alternative to beat reception of sustained wave signals, an arrangement is explained wherein the amplifying ratio of a repeating audion is varied periodically at an audio frequency. Coupled to this system is a simple audion detector. Musical signals of any desired pitch are thus obtained.

It is found that static of large amplitude nearly always decreases the wing current, while a signal (with beat reception) alternately increases and decreases it. A system of circuits is described whereby this fact is taken advantage of in balancing out static while retaining an additive response to signals, thus effecting an elimination of static to a considerable extent.

Finally, instances of long distance stations received and interference overcome in practice are given.

DISCUSSION

Lee de Forest (by letter): Absence from New York and stress of business prevents my giving to Mr. Armstrong's paper the thorough discussion it merits from me. Briefly, I must state that my investigation of the simple audion detector, the audion amplifier, and the "ultraudion" detector for undamped waves do not bear out completely the results and conclusions announced by that writer.

In the first place, anyone who has had considerable experience with numerous audion bulbs must admit that the behavior of different bulbs varies in many particulars, and to an astonishing degree. The wing-potential/wing-current curves for different bulbs, or even for the same bulb at different times, under differing conditions (filament temperature, etc.) vary widely. What may appear to be a fixed law for one bulb may not hold for another.

Mr. Armstrong makes no mention of this well-known fact; nor does he even state that his grid-potential/wing-current curve may be quite otherwise than he has shown it with different applied "B" battery voltage, or filament temperatures.

He makes no mention of the fact, often demonstrated, that a continuous-current indicating instrument, e.g., a micro-ammeter, may show a decrease in deflection, or practically no change in deflection either way when fairly strong radio frequency (or audio frequency) impulses are delivered to the grid even when the telephone receiver in the wing circuit gives strong response.

I have frequently proven that a *positive* charge applied to the grid, may decrease, rather than increase the "wing current." If I may say so, he treats the entire subject in much too cursory and cavalier a manner, even as he appears to be quite oblivious of the work of any other investigator or discoverer.

As I stated in an article in the *Electrical World,* February 20th, the *oscillating* quality of the audion was discovered by me several years ago.

I found that the complicated circuits Mr. Armstrong illustrates were quit unnecessary for producing the effects mentioned. In fact, the combination of oscillating and amplifying functions in the same bulb are obtained almost, if not quite, as efficiently, and far more simply by much simpler circuits.

The second method he shows for a combination tuning to radio and audio frequencies is ingenious and highly creditable. Unfortunately, as he truly points out, there is today no continuous wave generator of sufficiently constant frequency to permit full advantage being taken of this elegant method.

Edwin H. Armstrong: The condition in which a positive potential applied to the grid produces a decrease in the wing current is a remarkable one, in that it has been the cause of that mysterious atmosphere with which the audion has long been surrounded. The effect occurs under certain conditions which are easily explained. Suppose there is an appreciable amount of gas in the tube and the difference of potential between the wing and filament is adjusted so that a considerable number of positive ions is produced. In such a state it frequently happens that the number of positive ions coming in contact with the grid is in excess of the number of negative ions. As a consequence of this the grid assumes a positive charge with respect to the filament. Suppose the potential to which the grid becomes charged is three volts positive with respect to the negative terminal of the filament. Under these conditions a battery of say one or two volts connected as shown in Figure 1 with its positive terminal connected to the grid will really change the potential of the grid in the negative sense.

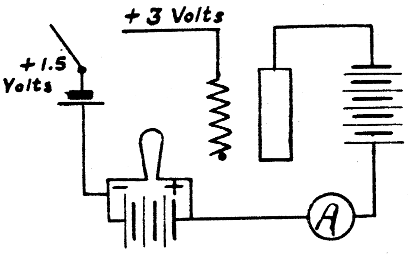

FIGURE 1

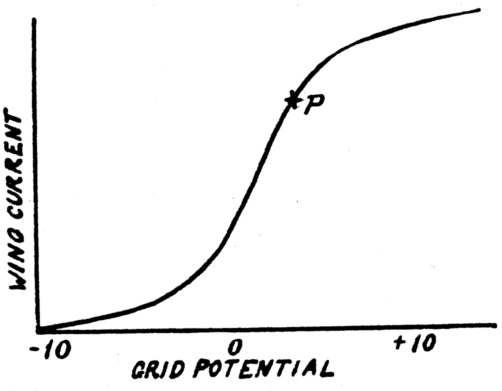

FIGURE 2

The natural result is a decrease in the wing current. The converse of this effect: the condition in which a negative potential applied to the grid produces an increase in the wing current is invariably met with in high vacuum audions where the potential assumed by the grid is invariably negative. Both cases, however, can be explained on the same grounds. Figure 2 shows the potential assumed by the grid when a large number of positive ions are present.

Edwin H. Armstrong (by letter): In replying to Dr. de Forest's communication, I want to point out that the paper was intended to deal with the application of circuits of a new type to the actuation of the audion. The fundamental operating features of the audion itself were outlined purely as a basis on which to explain the action of the circuits. A detailed explanation of the various phenomena involved in the audion as a detector and as a relay, radically different from that previously advanced by Dr. de Forest, was published by me some time ago in the *Electrical World,* December 12th, 1914, and the columns of that paper, are, no doubt, still open to discussion of these elementary matters.

Dr. de Forest speaks of the great differences existing between the wing potential-wing current curves. It will be readily understood by those familiar with the laws of the conduction of electricity thru gases that such is bound to be the case where any considerable amount of gas is present in the bulb. The potential at which progressive ionization of the gas begins, is dependent, among other things, on the pressure; and hence the upper parts of the wing-potential/wing-current curves vary, but the lower parts, *the only place where the electron relay can be operated*, are invariably of the same general shape. With the modern methods now available, for producing very high vacua, it is a simple matter to construct audions whose characteristics are for all practical purposes identical. With these high vacuum bulbs, the astonishing differences of which Dr. de Forest speaks disappear to an astonishing extent.

The great differences which sometimes exist between the grid-potential/wing-current curves of different audions or for the same audion under different conditions of wing potential or filament temperature are again due to the residual gas, and are eliminated as before by the use of very high vacua. It will be evident, of course, that for each value of wing potential and filament temperature there will be a different grid-potential/wing-current curve; but for high vacuum bulbs these curves lie one above the other in an orderly manner and, barring minor differences, are of the same general shape.

For an explanation of the fact that a continuous current instrument in the wing circuit shows no change in deflection when an alternating e.m.f. of *audio* frequency is impressed on the grid even when a telephone in the circuit with the meter gives a strong response, I want to call attention to Figures 2 and 5, of the original paper, together with a suggestion that a telephone perhaps is apt to respond somewhat more strongly to a alternating current than does a continuous current instrument! An explanation of the decrease of wing current which may occur will be found in the publication in the *Electrical World,* December 12th, 1914, with an accompanying oscillogram which shows the asymmetric effect in question.

The circumstance state by Dr. de Forest in which a *radio* frequency e.m.f. impressed on the grid produces a response in a telephone but not in a continuous current instrument is an impossible one. If the telephone responded, and there were no changes in the reading of the instrument, it would be an indication of an alternate and equal increase and decrease of the wing current at an audio frequency rate. This is an effect which *radio* frequency oscillations applied to the grid cannot produce. When a condenser is used in connection with the grid, radio frequency oscillations invariably produce a net decrease in the wing current and hence a decrease in the telephone current.

Where use is made of the asymmetric relaying, which is possible because of the bends in the operating characteristic, either a net increase or net decrease may be produced in the wing current by radio frequencies applied to the grid, depending at which bend the audion is worked, but an increase and decrease can never be produced at the same time.

Dr. de Forest attempts to throw doubt on the validity of the operating characteristic, and hence on all explanations depending thereon, by stating that he has frequently proven that a positive charge applied to the grid may decrease rather than increase the wing current, a contention originally advanced by him in explanation of the relay and detecting action of the audion. In the discussion, I have pointed out the fallacy in this view and explained the seeming paradox which is found in low vacuum bulbs on the working part of the grid-potential/wing-current curve. There is another effect which may lead to incorrect conclusions concerning the action of the electron relay, which is due to effects found above the working part of the curve. As the potential of the grid is increased, it is possible that the wing current may reach a maximum and then fall off. This is due to the fact that a conduction current flows to the grid when it is positive with respect to the filament, and that under certain conditions, this current is subtracted from the wing current.

The maximum current which can flow from filament to wing is limited to the number of electrons emitted by the filament, and if the condition of maximum current flow in the wing circuit is established before the grid potential becomes highly positive, then a further increase in the grid potential will increase the number of electrons absorbed by the grid and the result is a decrease in the wing current. The impossibility of working an electron relay on this part of the curve will be evident from the accompanying diagrams (Figure 3) which show how the effective resistance of the input side of the audion increases as the potential of the grid is varied.

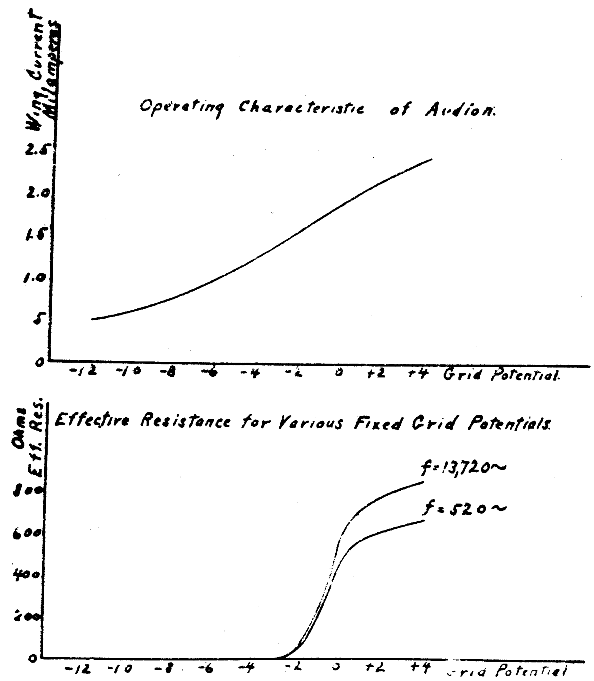

FIGURE 3

Only when the grid is negative with respect to the filament can the full amplifying power of the audion be realized, as the input side consumes no energy. Herein lies the explanation of the great differences which exist in the amplifying powers of different bulbs when used in the customary fashion. It is usual to operate the audio frequency amplifier with the grid insulated from the filament for conduction currents so that the potential of the grid is determined solely by the characteristics of the audion. If it should chance to be sufficiently negative, the input side consumes no energy and the result is a good one; if it should be positive, then the input side consumes energy and the amplification is seriously impaired, the degree depending on the value of the positive charge. All this is clearly supported by the fact that when the potential of the grid of a good bulb is arbitrarily made positive, the amplification falls off. The curves shown in Figure 3 are additional confirmation, and in this connection it is interesting to note the agreement between the radio and audio frequency curves.

The statement by Dr. de Forest that he originally discovered the oscillating phenomenon and applied it to producing the effects described several years ago cannot be here discussed, because his priority in this matter will be contested shortly in another way.

Lee de Forest (by letter): While I cannot accept Mr. Armstrong's explanations of my observations as to the action of a positively charged grid on the wing current, they have at least more to recommend them than has his previous flat contradiction that such an effect as I have described existed at all.

What Mr. Armstrong states are "elementary matters" have not appeared so to associates and collaborators of Drs. Rutherford and Soddy with whom I have discussed them. These discussions, however, were prior to the appearance of Mr. Armstrong's paper.

In spite of Mr. Armstrong's explanations, we are left quite in the dark as to how high these consistent vacua are, and just what operating voltages he refers to. More quantitative explicitness and citations of the exact performances of scores of bulb would be more convincing than are the theories proposed as a basis for description of sundry complicated circuits.

If he is dealing with a type of tube which is quite distinct from the audion (on account of the degree of vacuum, the applied potentials, etc.), this should have been explicitly stated at the outset. This is my chief complaint. No essential data are given, but only general laws with attempted axioms. I assumed that we were dealing with phenomena in the audion as popularly known, operating on from 20 to 50 volts. With such, at least, there still remain some unexplained problems.

If he be unable to explain my observation that, using audio frequencies, certain bulbs show a decrease, others no perceptible change in deflection of a direct current micro-ammeter while a telephone receiver gives responses many times audibility, this fact should be frankly stated. I should also like to have his explanation as to why certain audions are distinctly more sensitive to low than to high spark frequencies while others show the exact reverse. Though I have theories on this point, I have not yet proven them.

In connection with Mr. Armstrong's insistence on the value of his oscillograms which were taken at audio frequencies because audio and radio frequency phenomena are identical in nature, I should like to call attention to his statement that "This is an effect which radio (as distinguished from audio) frequency oscillations applied to the grid cannot produce."

Is it not perhaps possible that where successive strongly damped wave trains of radio frequencies, have alternately positive and negative initial wave fronts, an alternating increase and decrease of wing current may occur which would, while giving loud signals in the telephone receiver, produce practically no change in deflection in a direct current micro-ammeter in series therewith?

As to Mr. Armstrong's closing remark, I had not before realized that he actually claimed broadly the discovery of the oscillating property of the audion. I think it can and will be established that this was discovered some time before his first work in this field. If any are still of the opinion that the oscillating quality of the audion awaited the discovery of the complicated circuits he describes, I would refer them to the article on "The Double Audion Type of Receiver," by Professor A.H. Taylor, in the *Electrical World* of March 13th, 1915.

Edwin H. Armstrong (by letter): Replying to Dr. de Forest's latest communication in regard to the effect of a charged grid on the wing current, I cannot but assume, from his failure to produce evidence to the contrary, that his observations may be explained by the residual positive charge on the grid. This applies to that type of tube in which so many "unexplained" phenomena are observed: "the audion, as popularly known, operating on from 20 to 50 volts."

Dr. de Forest's misapprehension as to the type of tube referred to in the paper rests entirely with himself. It was definitely stated in the article in the *Electrical World*, and on the occasion of the presentation of this paper before the Institute of Radio Engineers that the vacuum of the bulbs was such that only thermionic currents existed. The methods used to obtain these vacua were those recently described by Dr. Irving Langmuir in a paper presented before the American Physical Society, and also in another paper presented before the Institute of Radio Engineers. (See the issue of the *Proceedings*, together with the discussion on Dr. Langmuir's paper).

In explanation of Dr. de Forest's observation that audio frequencies applied to the grid may produce either a decrease or no change in the reading of a *direct* current micro-ammeter, while a telephone responds strongly, I have pointed out that the oscillograms which fully explain both cases. It seems necessary to add that a *direct* current instrument of the type mentioned measures *average* values!

The question of the relative sensitiveness of an audion as a detector to high and low spark frequencies is entirely irrelevant to the present discussion. It has, however, some points which are of interest. The effect occurs only when the valve action of the audion is used to rectify the oscillations and a condenser is necessarily used in series with the grid. When there is a scarcity of positive ions, the rate of leak of the charge accumulated in the grid condenser from one group of oscillations may be so slow that the condenser fails to clear itself before the arrival of another group of oscillations. Under these conditions, a residual negative charge is continuously maintained in the grid condenser during the periods of signaling, and this charge interferes with the rectifying action between the grid and filament. Obviously, this effect will be more pronounced at the high spark frequencies, and the sensitiveness of the audion will be less impaired on the low spark frequencies. The phenomenon is an interesting one, but on the whole it is quite simple and elementary in character.

Dr. de Forest attempts to explain the circumstance which I have shown is impossible, the circumstance in which radio frequencies applied to the grid produce response in a telephone in the wing circuit but no change in the deflection of a continuous current instrument in series with the telephone. The explanation advanced is impossible. The effect described could be produced only by wave trains that were practically aperiodic. Needless to say, nothing remotely approaching this is in use in radio telegraphy at the present time.

In conclusion, I wish to point out that this discussion was originally begun by Dr. de Forest in an attempt to invalidate the explanations advanced to account for the various detecting, repeating, and oscillating phenomena. It is my opinion that the explanations given stand as correct.

Robert H. Marriott: It has frequently been charged that there has been a lack of research in radio engineering carried out in physical research laboratories. Mr. Armstrong deserves much praise in carrying out his highly interesting investigation, and it is to be hoped that further valuable results will be obtained under similar auspices.

(This discussion is herewith closed.)

REFERENCES

The introductory material of this paper was originally submitted as a discussion by letter on Haraden Pratt's paper, "Long Range Reception with Combined Crystal Rectifier and Audion Amplifier." The first six figures have been kindly lent by the *Electrical World*; the remaining figures and text are herewith published for the first time.)

2. *Electrical World*, December 12, 1914; and also discussion in *London Electrician*, between Reisz and de Forest on the difference between electron and gas relays. (February 6, 1914, page 726; March 13, 1914, page 956; June 12, 1914, page 402; July 3, 1914, page 538; and July 31, 1914, page 702.Editor.)

DISCLOSURE OF THE REGENERATIVE CIRCUIT

by **Edwin Howard Armstrong**

Author's Note: *The substance of the following account is of the disclosure of the regenerative circuit to the leading engineers of the American Telephone and Telegraph Company in February and April of 1914.*

Shortly after my graduation from Columbia University as an electrical engineer in 1913 the University decided to set up a course of instruction in radio. I was given the job of assistant in the Depart- ment of Electrical Engineering by Professor Walter I. Slichter, who evidently thought that I had absorbed enough of his course on Alternating Current Theory to qualify me, and went to work in the laboratory of Professor Michael I. Pupin, then a world renowned figure in the field of communications. A small antenna was set up on the campus between two of the buildings and we went to work on the course. In the latter part of 1913 I found the time to bring the regenerative circuit apparatus down from my home in Yonkers to the Marcellus Hartley Research Laboratory and to give a series of demonstrations for the leading communication companies.

Professor Pupin happened be around late one evening when darkness covered the path to Hawaii, so the signals from the Poulsen arc station were coming in very well. Professor Pupin, who had been a close friend of Marconi since his first lecture in this country, and who had warmly sponsored Marconi's objectives for many years, became highly enthusiastic about the demonstration. Shortly thereafter he chanced to meet a group of acquaintances at the University Club in New York City, among whom was J. J. Carty, then chief engineer of the American Telephone and Telegraph Company. He related the story of the demonstration, and I do not doubt that it was a most animated account.

Mr. Carty at the time said nothing. But on the next get-together of the same group Mr. Carty remarked that Pupin had quite successfully "pulled his leg" at the time but he had since been able to consult his radio staff about the matter, and he now was in a position to say that the story Pupin told was impossible.

This pronouncement was met with prompt rejoinder by Professor Pupin to come to the laboratory and see the "impossible". On the evening of February 6, 1914, Mr. J. J. Carty, Mr. Bancroft Gherardi and Dr. F. B. Jewett, then the leading engineers at the A. T. & T., visited the Marcellus Hartley Research Laboratory for a demonstration. They brought along a young fellow by the name of Lloyd Espenschied to read the signals and check up on the identification of the stations which were heard. The demonstration was successfully carried out, and as usual without disclosing the circuit connections or how the apparatus functioned.

The spark signals were, of course, heard with their natural tone and so excited no particular comment. The arc signals, however, had the assembled company much puzzled. Signaling on the Poulsen arc at that time was carried out by varying the frequency of the arc a few percent, and at the low frequencies then employed for transmission (approximately 50,000 cycles) the "back wave" was generally audible for the best adjustment of the receiver. I well remember Mr. Carty's asking about it and his humorous comment that "It sounds like an 'inebriated' flute player".

On April 25, 1914, at a further demonstration of the equipment, a full disclosure of the principles of operation was made to Mr. Gherardi, Dr. Jewett, and Mr. E. H. Colpitts. These demonstrations and disclosures brought about the entry of the American Telephone and Telegraph Company into the field of communication by radio. From that date its radio staff, which then consisted of Lloyd Espenschied and the late Austin Curtis, began the never-ending expansion that has resulted in the amazing organization of today.

THE SUPERHETERODYNE CIRCUIT

A NEW METHOD FOR THE RECEPTION OF WEAK SIGNALS AT SHORT WAVE LENGTHS...
E. H. Armstrong, *Proc. of The Radio Club of America*,
Vol. 1, No. 1, Jan 1920

A NEW SYSTEM OF SHORT WAVE AMPLIFICATION... Edwin H. Armstrong,
Proc. of the Institute of Radio Engineers, Vol. 6, 1920

THE STORY OF THE SUPERHETERODYNE... Edwin H. Armstrong,
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WHO INVENTED THE SUPERHETERODYNE ?... Alan S. Douglas

ON THE ORIGIN OF THE SUPERHETERODYNE... Walter Schottky,
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ON THE SUBJECT OF THE SUPERHETERODYNE... Lucien Levy, *L'Onde Electrique*, 1955

PROBABLY A WHOLE LOT MORE THAN YOU EVER WANTED TO KNOW ABOUT THE SUPERHETERODYNE RECEIVER... Ed Lyon

A New Method for the Reception of Weak Signals at Short Wave Lengths

By E. H. Armstrong

At Meeting of the Radio Club of America, Columbia University,
December 19, 1919

THE problem of receiving weak signals of short wave length in a practical manner has become of great importance in recent years. This is especially true in connection with direction finding work where the receiver must respond to a very small fraction of the energy which can be picked up by a loop antenna.

The problem may be summed up in the following words:— construct a receiver for undamped, modulated continuous and damped oscillations which is substantially equally sensitive over a range of wave length from 50-600 meters; which is capable of rapid adjustment from one wave to another, and which does not distort or lose any characteristic note or tone inherent in the transmitter.

It is, of course, obvious that some form of amplification must be used but a study of the various known methods soon convinces one that a satisfactory solution cannot be obtained by any direct method. In the interests of completeness we will consider the three well known direct means which might possibly be employed, and examine the limitations which apply to each. These three methods are:—

(1) Amplification of the low frequency current after rectification;

(2) Amplification of the high frequency current before rectification; and

(3) Application of the heterodyne principle to increase the efficiency of rectification.

Consider first the method of rectifying the high frequency current and amplifying the resulting low frequency current. Two limitations at once present themselves, one inherent in low frequency amplifiers and the other inherent in all known rectifiers. The limitation in the amplifier is the residual noise which makes it impractical to use effectively more than two stages of amplification. The second limitation lies in the characteristic of the detector or rectifier. All rectifiers have a characteristic such that the rectified or low frequency current is roughly proportional to the square of the impressed high frequency E. M. F. Hence the efficiency of rectification becomes increasingly poorer the weaker the signal until a point is reached below which the detector practically ceases to respond.

The second method of attack on the problem is the amplification of the received high frequency currents before rectification to a point where they can be efficiently dealt with by the detector. This method is ideal on long waves and various methods of inductance, resistance and capacity couplings have been successfully used, but when the attempt is made to use the same methods of coupling on wave lengths from 200 to 600 it results in complete failure. This is because the low capacity reactance existing between the various elements of the tubes causes them, in effect, to act as a short circuit around the coupling means and thereby prevent the establishment of a difference of potential in the external plate circuit. It is, of course, possible to eliminate the short-circuiting by tuning with a parallel inductance but this introduces a complication of adjustment which is highly objectionable and the tuning of all circuits also leads to difficulty with undesirable internal oscillations.

The third method which might be used is the heterodyne method to increase the efficiency of rectification. Great increase in signal strength is possible by means of this method, particularly where the signal is very weak but there are certain reasons why it cannot be effectively used in practice at the present time. The chief reason in receiving continuous waves of short wave length is the instability of the beat tone which makes operations below 600 meters unsatisfactory. This disadvantage does not apply to the reception of spark signals but here the loss of the clear tone and its individuality offsets much of the gain due to increased signal strength. In the case of telephony the distortion which always results likewise offsets the gain in strength. It is, of course, undeniable that there are many special cases where the use of the heterodyne on short wave length is of the greatest advantage but the foregoing remarks apply to the broad field of commercial working where the practical aspects of the case greatly reduce the value of the amplification obtained by this method.

In spite of the great difficulties involved in a direct solution great success was obtained by Round in England and Latour in France in the production of high frequency amplifiers to cover effectively a range from 300 to 800 meters. This result was accomplished only by the most painstaking and careful experiment and it represents some of the very finest radio work carried out during the war. Round secured his solution by constructing tubes having an extremely small capacity without increase in internal resistance above normal values and coupling the tubes by means of transformers wound with very fine wire to keep down the capacity and very high resistance to prevent oscillation at the resonant frequency of the system. The effect of the high ratio of inductance to capacity and the high resistance of the winding is all to flatten the resonance curve of the system and widen the range of response. Latour solved the problem by the use of iron core transformers wound with very fine wire, the iron serving the double purpose of increasing the ratio of inductance to capacity and introducing resistance into the system. Both these factors widen the range of response.

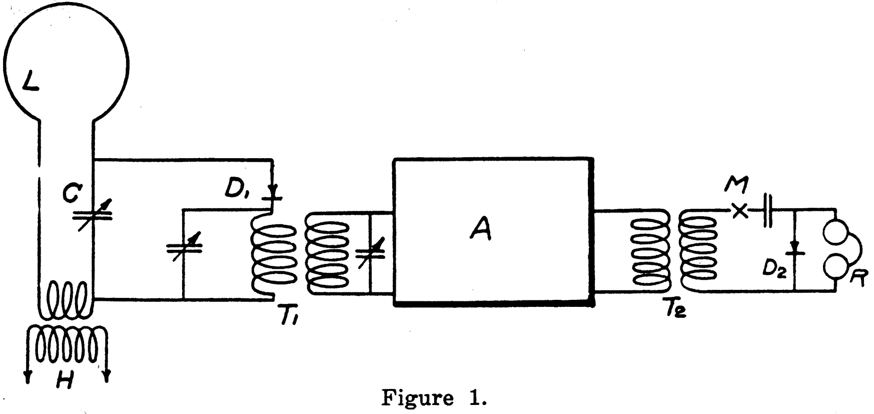

Figure 1.

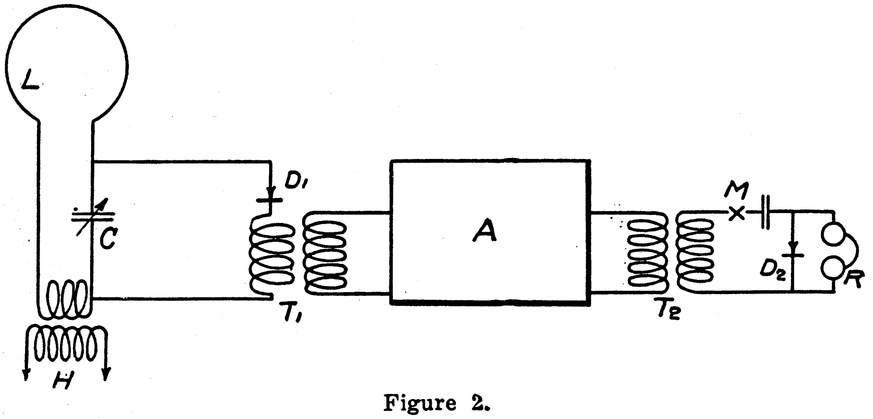

Figure 2.

It is the purpose of this paper to describe a method of reception evolved at the Division of Research and Inspection of the Signal Corps A. E. F. which solves the problem by means of an expedient. This expedient consists in reducing the frequency of the incoming signal to some predetermined superaudible frequency which can be readily amplified, passing this current through an amplifier and then detecting or rectifying the amplified current. The transformation of the original high frequency to the predetermined value is best accomplished by means of the heterodyne and rectification, and the fundamental phenomena involved will be understood by reference to the diagram of Fig. 1. Here L C represents the usual tuned receiving circuit, loop or otherwise, H a separate heterodyne and D_1 a rectifier. A is a high frequency amplifier designed to operate on some predetermined frequency. This frequency may be any convenient frequency which is substantially above audibility. The amplifier is connected on its input side to the rectifier D and on its output side to a second rectifier D_2 and a telephone or other receiver.

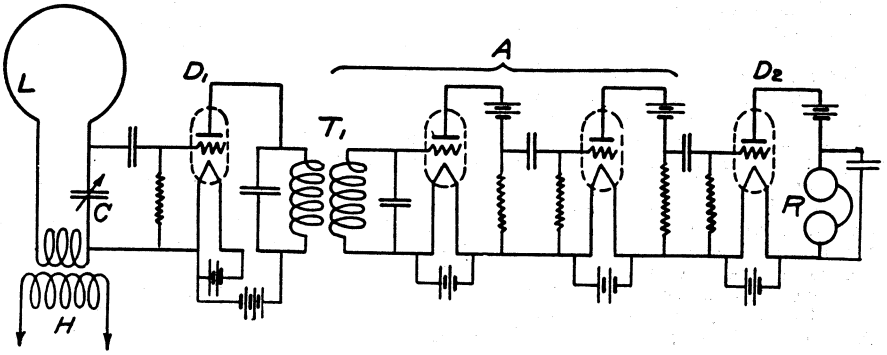

Figure 3.

Suppose that the frequency to be received is 3,000,000 cycles or 100 meters and, for the sake of simplicity, that the incoming waves are undamped. Also, assume that the amplifier A has been designed for maximum efficiency at 100,000 cycles per second. The circuit LC is tuned to 3,000,000 cycles and the heterodyne H is adjusted to either 3,100,000 or 2,900,000 cycles either of which will produce a beat frequency of 100,000 cycles per second. The combined currents of 3,000,000 and 3,100,000 (or 2,900,000) cycles are then rectified by the rectifier D_1 to produce in the primary of the transformer T_1 a direct current with a riding 100,000 cycles component. This 100,000 cycles current is then amplified to any desired degree by the amplifier A and detected or rectified by D_2. In order to get an audible tone where telephone reception is used some form of modulation or interruption must, of course, be employed in connection with this second rectification as the current in the output circuit of the amplifier is of a frequency above audibility. While this frequency is only 100,000 cycles and while it is therefore well within the range of practical heterodyning, its steadiness depends on the beats between 3,000,000 and 3,100,000 cycles per second and hence in any attempt to heterodyne it to audibility the same difficulties due to fluctuation would be encountered as in heterodyning the original high frequency to audibility. However, the inability to use the heterodyne on the second rectification is not of great importance because the amplitude of the signal to be rectified is large and hence the difference (as far as signal strength in the telephone is concerned) between heterodyne and modulated reception is not great.

It is important to note here that the value of the heterodyne in the first rectifier should always be kept at the optimum value in order to ensure the carrying out of the first rectification at the point of maximum efficiency. This adjustment, however, is not a critical one and once made it is seldom necessary to change it. The amplifier A may be made selective and highly regenerative if so desired and a very great increase in the selectivity of the system as a whole can be secured. Fig. 2 illustrates the principle involved. This arrangement is substantially the same as Fig. 1 except that the primary and secondary coils of the transformer T_1 are tuned by means of condensers as shown and the coupling between them is reduced to the proper value to insure sharp tuning. This system of connection has all the advantages of tuning to the differential frequency in the manner well known in the art and an additional one due to the fact that since it is above audibility the musical character of atmospheric disturbances so troublesome in low frequency tuning, does not appear.

So far, the reception of undamped waves only has been considered but this method of amplification is applicable also to the reception of damped wave telegraphy and to telephony with practically equal efficiency and without distortion of any characteristic of tone. It is somewhat difficult to understand this, particularly in the case of the reception of spark signals as in all previous experience the heterodyning of a spark signal has resulted in the loss of the note, whereas in the present case the individuality between stations is more marked even than on a crystal rectifier.

This is the most interesting point in the operation of the system and the reason will be understood from the following analysis:

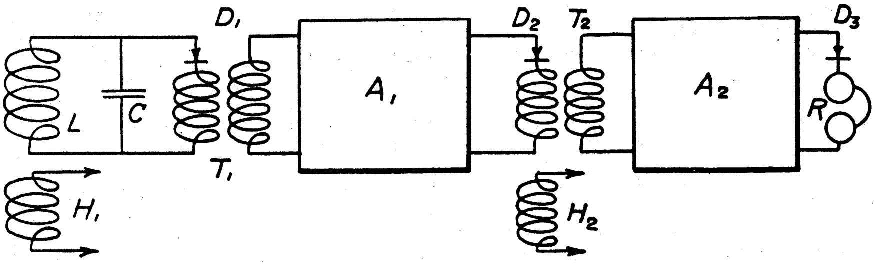

Figure 4.

In heterodyning, the efficiency of rectification of the signaling current depends on its phase relation with the local current. If the two currents are either in phase or 180° out of phase the efficiency of rectification is a maximum; if 90° out of phase a minimum. In ordinary heterodyning the initial phase difference depends on the time of sparking at the transmitter and hence this initial phase difference will be different for each wave train. As the frequency of the two currents are substantially the same and as the duration of a wave train is short compared to the time necessary to produce a complete beat at an audible frequency, this initial phase difference is maintained throughout the wave train. Hence, the different wave trains are rectified with varying efficiency, the telephone current becomes irregular and a rough or hissing tone results.

In the present method of heterodyning the beat frequency is high so that several beats per wave train are produced. As a consequence, the phase angle between the signaling and local currents varies through several cycles and the initial phase difference becomes a matter of minor importance. The number of beats which actually occur in practice depends on the beat frequency, the damping of the incoming wave and the damping of the receiving circuit. As the damping of the receiving circuit is almost invariably much less than the damping of the incoming wave it is the determining factor. In any practical case, however, where the beat frequency is kept above 20,000 cycles there is a sufficient number of beats to minimize the initial phase differences and maintain the characteristic tone.

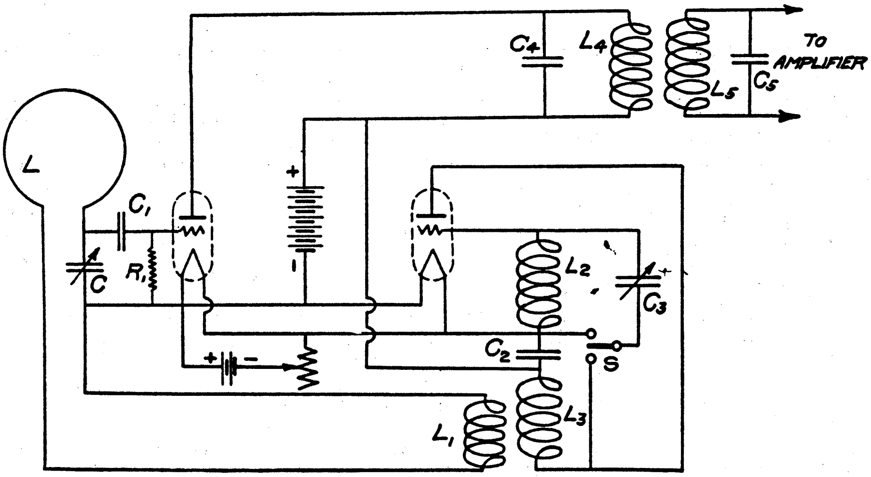

Figure "A"

The phenomena which occur in the reception of modulated continuous wave telegraphy and telephony are substantially a combination of those explained in the cases of undamped and damped wave reception. The adjustments are made in the same manner as for damped waves and the only precaution necessary in the reception of telephony is to damp the amplifier circuits somewhat to prevent distortion of the speech by excessive resonance.

The arrangement found most suitable for practical working is shown in Fig. 3. Both rectifications are carried out by three element vacuum tubes. The amplifier here shown is resistance coupled, although any form of coupling may be used. The tuned circuits L_1C_1 and L_2C_2 are preferably adjusted to some frequency between 50,000 and 100,000 cycles. The circuit LC may be made regenerative if so desired by any form of reactive coupling but the practicability of this depends largely on the amount of time which is available for making adjustments.

In the diagram of Fig. 3 only two stages of high frequency amplification are shown but at least four and preferably six should be used to get the maximum advantage of this method. This is because the transformation of frequency is accomplished only by a certain loss so that something between one and two stages of amplification is required before this is overcome and it is possible to realize a gain. In this figure a separate heterodyne is shown and it will generally be necessary to use it on account of the mistuning which is involved in the use of the self heterodyne. This mistuning is considerable on 600 meters but on the shorter waves it is possible to use the self heterodyne method with equal efficiency as far as signal strength is concerned and a great gain in simplicity, as adjustments have been reduced to the minimum of a single one.

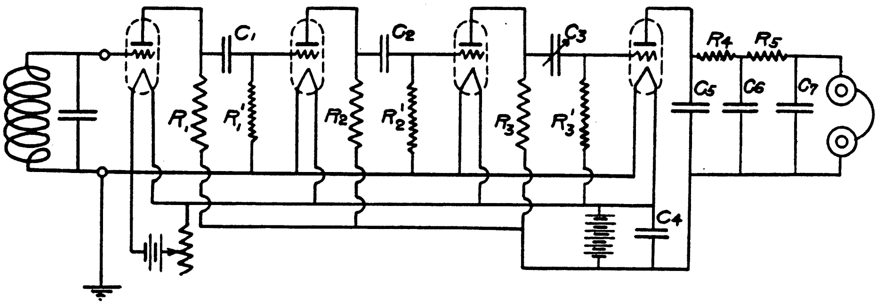

Figure "B"

It may be observed here that this method is not limited to one transformation of frequency with one subsequent amplification. If the frequency to be received is 5,000,000 cycles this may be stepped down to 500,000 cycles, amplified, stepped down again to 50,000 cycles, re-amplified and detected as illustrated by Fig. 4. The great advantage of this method of amplification is that the tendency to oscillate due to the reaction between the output of the amplifier and the input is eliminated as the frequencies are widely different. The only reaction which can take place is in each individual amplifier. Hence, the process of extreme amplification is best carried out in stages of several frequencies, the amplification on each frequency being carried as far as possible without loss of stability. As soon as the limit of stable operation is approached, no further amplification should be attempted until the frequency has been changed.

The foregoing descriptions and explanations do not pretend to any save a most superficial treatment of the phenomena present in this method of reception. Lack of time has prevented a careful study and quantitative data only of the roughest sort has been obtained. Sufficient work has been done, however, to demonstrate the value of the method particularly in the case of modulated continuous wave telegraphy and telephony. In this field neither the amplification nor the selectivity can be equalled by any direct method. The practice of this method involves the use of many known inventions but in connection with the production of a superaudible frequency by heterodyning I wish to make due acknowledgement to the work of Meissner, Round and Levy, which is now of record. The application of the principle to the reception of short wave is, I believe, new and it is for this reason that this paper is presented.

While the fundamental idea of this method of reception is relatively simple the production of the present form of the apparatus was a task of the greatest difficulty for reasons known only too well to those familiar with multistage amplifiers and to Lieutenant W. A. MacDonald, Master Signal Electricians J. Pressley and H. W. Lewis and Sergeant H. Houck, all of the Division of Research and Inspection Signal Corps A. E. F., I wish to give full credit for its accomplishment.

ADDENDUM.

For the purpose of facilitating the construction of an amplifier suitable for short wave lengths, Figures A and B are added to the original paper, and such values as can be specified are given. The constants of the loop and heterodyne coils depend, of course, on the particular range which it is desired to cover, but this is readily obtained by trial.

Fig. A.
C=.0005 mfds. max.
C_1=.0005 mfds.
R_1=1 megohm
L_1=about 1/20 L
C_4 and C_5=.001 mfds.
L_4 and L_5=50 millihenrys
C_2=.1 mfd.
C_3=.0005 mfds. max.
Fig. B
R_1 R_2 and R_3=50,000 ohms
R_1' R_2' R_3'=1 megohm
C_1 and C_2=.0005 mfds.
C_3=.0005 mfds. max.
C_4=.1 mfd.
C_5 C_6 and C_7=.005 mfds.
R_4 and R_5=12,000 ohms.

NOTE. The purpose of the filter is to keep the radio frequency currents out of the telephone cords and thereby prevent reaction on the input side of the amplifier with resulting oscillations. This filter is not always necessary and it will frequently be possible to cut out one or both stages.

With an amplifier consisting of six Type V tubes plus two tubes in the frequency transformer, or eight in all, it has been possible to receive the signals of amateur stations in Texas on a three foot loop.

Hartley Research Laboratory,
Columbia University.

A NEW SYSTEM OF SHORT WAVE AMPLIFICATION

By **Edwin H. Armstrong**
Marcellus Hartley Research Laboratory,
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Presented before The Institute of Radio Engineers, New York, January 12, 1920
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The problem of receiving weak signals of short wave length in a practical manner has become of great importance in recent years. This is especially true in connection with direction finding work where the receiver must respond to a very small fraction of the energy which can be picked up by a loop antenna.

The problem may be summed up in the following words: -- to construct a receiver for undamped, modulated continuous, and damped oscillations which is substantially equally sensitive over a range of wave lengths from 50 to 600 meters, which is capable of rapid adjustment from one wave to another, and which does not distort or lose any characteristic note or tone inherent in the transmitter.

It is, of course, obvious that some form of amplification must be used, but a study of the various known methods soon convinces one that a satisfactory solution cannot be obtained by any direct method. In the interest of completeness, we will consider the three well-known direct means which might possibly be employed, and examine the limitations which apply to each. These three methods are: --

(1) Amplification of the audio frequency current after rectification;

(2) Amplification of the radio frequency current before rectification; and

(3) Amplification of the heterodyne principle to increase the efficiency of rectification.

Consider the first method of rectifying the radio frequency current and amplifying the resulting audio frequency current. Two limitations at once present themselves, one inherent in audio frequency amplifiers, and the other inherent in all known rectifiers. The limitation in the amplifier is the residual noise which makes it impractical to use effectively more than two stages of amplification. The second limitation lies in the characteristic of the detector or rectifier. All rectifiers have a characteristic such that the rectified or audio frequency current is roughly proportional to the square of the impressed radio frequency emf. Hence the efficiency of rectification becomes increasingly poorer the weaker the signal until a point is reached below which the detector practically ceases to respond.

The second method of attack on the problem is the amplification of the received radio frequency currents before rectification to a point where they can be efficiently dealt with by the detector. This method is ideal on long waves, and various methods of inductance, resistance, and capacity couplings have been successfully used, but when the attempt is made to use the same methods of coupling on wave lengths below 600 meters, it results in complete failure. This is because the low capacity reactance existing between the various elements of the tubes causes them, in effect, to act as a short circuit around the coupling means and thereby prevents the establishment of a difference of potential in the external plate circuit. It is, of course, possible to eliminate the short-circuiting by tuning with a parallel inductance but this introduces a complication of adjustment which is highly objectionable and the tuning of all circuits also leads to difficulty with undesirable internal oscillations.

The third method which might be used is the heterodyne method to increase the efficiency of the rectification. Great increase in signal strength is possible by means of this method, particularly where the signal is very weak, but there are certain reasons why it cannot be effectively used in practice at the present time. The chief reason in receiving continuous waves of short wave length is the instability of the beat tone which makes operations below 600 meters unsatisfactory. This disadvantage does not apply to reception of spark signals but here the loss of the clear tone and its individuality offsets much of the gain due to increased signal strength.

In the case of telephony the distortion which always results likewise offsets the gain in strength. It is, of course, undeniable that there are many special cases where the use of the heterodyne on short wave lengths is of the greatest advantage but the foregoing remarks apply to the broad field of commercial working where the practical aspects of the case greatly reduce the value of the amplification obtained by this method.

In spite of the great difficulties involved in a direct solution, great success was obtained by Round in England and Latour in France in the production of radio frequency amplifiers to cover effectively a range from 300 to 800 meters. This result was accomplished only by the most painstaking and careful experiment and represents some of the very finest radio work carried out during the war.

Round secured his solution by constructing tubes having an extremely small capacity without increase in internal resistance above normal values and coupling the tubes by means of transformers wound with very fine wire to keep down the capacity and very high resistance to prevent oscillation at the resonant frequency of the system. The effect on the high ratio of inductance to capacity and the high resistance of the winding is to flatten the resonance curve of the system and widen the range of response. Latour solved the problem by the use of iron core transformers wound with very fine wire, the iron serving the double purpose of increasing the ratio of inductance to capacity and introducing resistance into the system. Both these factors widen the range of response.

It is the purpose of this paper to describe a method of reception evolved at the Division of Research and Inspection of the Signal Corps, American Expeditionary Force, which solves the problem by means of an expedient. This expedient consists in reducing the frequency of the incoming signal to some predetermined super-audible frequency which can be readily amplified, passing the current thru an amplifier, and then detecting or rectifying the amplified current.

The transformation of the original radio frequency is best accomplished by means of the heterodyne and rectification, and the fundamental phenomena involved will be understood by reference to Figure 1.

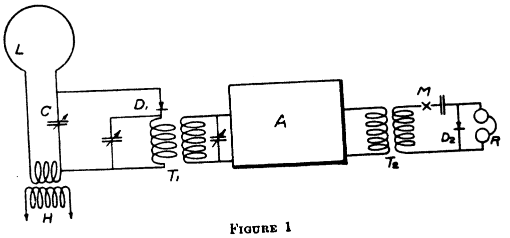

FIGURE 1

Here LC represents the usual tuned receiving circuit, loop or otherwise, H a separate heterodyne, and D_1 a rectifier. A is a radio frequency amplifier designed to operate on some predetermined frequency. This frequency may be any convenient frequency which is substantially above audibility. The amplifier is connected on its input side to rectifier D_1 and on its output side to a second rectifier D_2 and a telephone or other receiver.

Suppose now that the frequency to be received is 3,000,000 cycles per second corresponding to a wave length of 100 meters and, for the sake of simplicity, that the incoming waves are undamped. Also, assume that the amplifier A has been designed for maximum efficiency at 100,000 cycles per second. The circuit LC is tuned to 3,000,000 cycles, and the heterodyne H is adjusted to either 3,100,000 or 2,900,000 cycles either of which will produce a beat frequency of 100,000 cycles per second. The combined currents of 3,000,000 and 3,100,000 (or 2,900,000) cycles are then rectified by the rectifier D_1 to produce in the primary of the transformer T_1 a direct current with a superimposed 100,000-cycle component. This 100,000 cycle current is then amplified to any desired degree by the amplifier A and detected or rectified by D_2.

In order to get an audible tone where telephone reception is used some form of modulation or interruption must, of course,, be employed in connection with this second rectification of current in connection with this second rectification as the current in the output circuit of the amplifier is of a frequency above audibility. While this frequency is only 100,000 cycles and while it is therefore well within the range of practical heterodyning, its steadiness depends on the beats between 3,000,000 and 3,100,000 cycles per second and hence in any attempt to heterodyne it to audibility the same difficulties due to fluctuation would be encountered as in heterodyning the original frequency to audibility. However, the inability to use the heterodyne on the second rectification is not of great importance because the amplitude of the signal to be rectified is large and hence the difference (as far as signal strength in the telephone is concerned) between heterodyne and modulated reception is not great.

It is important to note here that the value of the heterodyne current in the first rectifier should always be kept at the optimum value to ensure the carrying out of the first rectification at the point of maximum efficiency. This adjustment, however, is not a critical one, and, once made, it is seldom necessary to change it. The amplifier *A* may be made selective and highly regenerative if so desired, and some very great increases in the selectivity of the system as a whole can be secured.

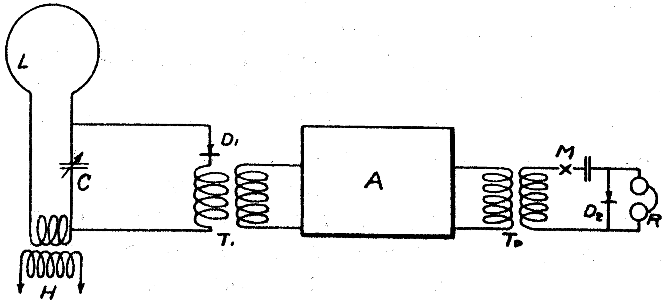

Figure 2

Figure 2 illustrates the principle involved. This arrangement is substantially the same as Figure 1 except that the primary and secondary coils of the transformer T_1 are tuned by means of condensers as shown and the coupling between them is reduced to the proper value to insure sharp tuning.

This system of connection has all the advantages of tuning to the differential frequency in the manner well known in the art and an additional one due to the fact that since it is above audibility the musical character of atmospheric disturbances so troublesome in audio frequency tuning, does not appear.

So far, the reception of undamped waves only has been considered, but this method of amplification is applicable also to the reception of damped wave telegraphy and to telephony with practically equal efficiency and without distortion of any characteristics of tone. It is somewhat difficult to understand this, particularly in the case of the reception of spark signals as in all previous experience the heterodyning of a spark signal has resulted in the loss of the note, whereas in the present case the individuality between stations is more marked even than on a crystal rectifier.

This is the most interesting point in the operation of the system and the reason will be understood from the following analysis:

> In heterodyning, the efficiency of rectification of the signaling current depends on its phase relation with the local current. If the two currents are either in phase or 180° out of phase the efficiency of rectification is a maximum; if 90° out of phase a minimum. In ordinary heterodyning, the initial phase difference depends on the time of sparking at the transmitter and hence this initial phase difference will be different for each wave train. As the frequency of the two currents are substantially the same, and as the duration of a wave train is short compared to the time necessary to produce a complete beat at an audible frequency, the initial phase difference is maintained thruout the wave train. Hence, the different wave trains are rectified with varying efficiency, the telephone current becomes irregular, and a rough or hissing tone results.

In the present method of heterodyning, the beat frequency is high so that several beats per wave train are produced. As a consequence, the phase angle between the signaling and local currents varies thru several cycles and the initial phase difference becomes a matter of minor importance. The number of beats which actually occur in practice depends upon the beat frequency, the damping of the incoming wave, and the damping of the receiving circuit. As the damping of the receiving circuit is almost invariably much less than the damping of the incoming wave, it is the determining factor. In any practical case, however, where the beat frequency is kept over 20,000 cycles per second there is a sufficient number of beats to minimize the initial phase differences and maintain the characteristic tone.

The phenomena which occur in the reception of modulated continuous wave telegraphy and telephony are substantially a combination of those explained in the cases of undamped and damped wave reception. The adjustments are made in the same manner as for damped waves and the only precaution necessary in the reception of telephony is to damp the amplifier circuits somewhat to prevent distortion of the speech by excessive resonance.

The general arrangement found most suitable for practical working is shown in Figure 3. Both rectifications are carried out by three-element vacuum tubes. The amplifier here shown is resistance coupled, although any form of coupling may be used. The tuned circuits LC and L_2C_2 are preferably adjusted to some frequency between 50,000 and 100,000 cycles. The circuit LC may be made regenerative, if so desired, by any form of reactive coupling, but the practicability of this depends largely on the amount of time which is available for making adjustments.

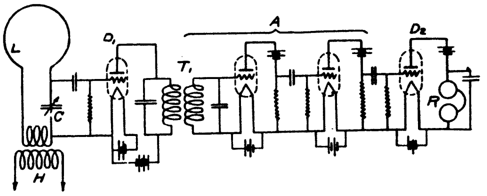

FIGURE 3

In the diagram of Figure 3, only two stages of radio frequency amplification are shown, but at least four and preferably six should be used to get the maximum advantage of this method. This is because the transformation of frequency is accomplished only by a certain loss so that something between one and two stages of amplification is required before this is overcome and it is possible to realize a gain. In this figure a separate heterodyne is shown, and it will generally be necessary to use it on account of the mistuning which is involved in the use of the self heterodyne. This mistuning is considerable on 600 meters but on the shorter waves it is possible to use the self heterodyne method with equal efficiency as far as signal strength is concerned and a great gain in simplicity, as adjustments have been reduced to the minimum of a single one.

It may be observed here that this method is not limited to one transformation of frequency with one subsequent amplification. If the frequency to be received is 5,000,000 cycles this may be stepped down to 500,000 cycles, amplified, stepped down again to 50,000 cycles, reamplified and detected. The great advantage of this method of amplification is that the tendency to oscillate due to the reaction between the output of the amplifier and the input is eliminated as the frequencies are widely different. The only reaction which can take place is in each individual amplifier. Hence, the process of extreme amplification is best carried out in stages of several frequencies, the amplification on each frequency being carried as far as possible without loss of stability. As soon as the limit of stable operation is approached, no further amplification should be attempted until the frequency has been changed.

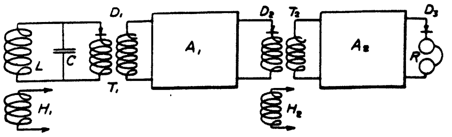

FIGURE 4

The foregoing descriptions and explanations do not pretend to be any save a most superficial treatment of the phenomena present in this method of reception. Lack of time has prevented a careful study and quantitative data only of the roughest sort has been obtained. Sufficient work has been done, however, to demonstrate the value of the method particularly in the case of modulated continuous wave telegraphy and telephony. In this field neither the amplification nor the selectivity can be equaled by any direct method.

The practical results which have been obtained may perhaps be of interest. With a ten-turn, three-foot (1 meter) loop antenna and an amplifier consisting of six stages, resistance coupled, making a total of eight tubes, the night signals of ships working with the Florida and Gulf stations are loudly received. The night signals of amateur stations in the Middle West are regularly received as are also the signals of stations in the Gulf States.

The general arrangement of the apparatus used is shown in Figures 5 and 6 which illustrate the scheme of connections of the frequency transformer and amplifier respectively. Four stages of amplification only are shown but six were actually used. It is beyond question much more efficient to use some form of inductive coupling since the amplifier is intended to operate on only one frequency and the use of a resistance coupled amplifier is not recommended where one of the former type is available.

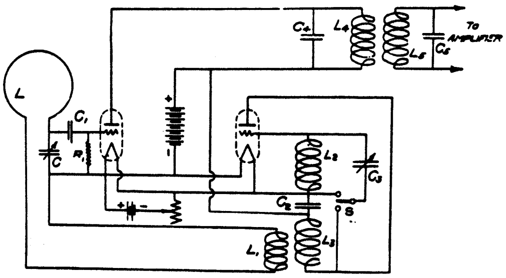

FIGURE 5

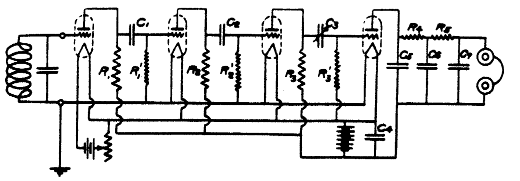

FIGURE 6

The new practice of this method involves the use of many known inventions, but in connection with the production of a superaudible frequency by heterodyning I wish to make due acknowledgment to the work of Meissner, Round, and Levy, which is now of record. The application of the principle to the rèception of short waves is, I believe, new and it is for this reason that this paper is presented.

While the fundamental idea of this method of reception is relatively simple, the production of the present form of the apparatus was a task of the greatest difficulty for reasons known only too well to those familiar with multistage amplifiers; and to Lieutenant W. A. MacDonald, Master Signal Electricians J. Pressby and H. W. Lewis, and Sergeant H. Houck, all of the Division of Research and Inspection, Signal Corps, A. E. F., I wish to give full credit for its accomplishment.

SUMMARY

The various possible known methods of amplifying incoming signals of very short wave length (below 600 meters) are described and their limitations considered

The new method then described consists (for continuous wave reception) of the following steps:-

1. Heterodyning, with the production of a beat frequency which is itself a *radio* frequency (for example, 100,000 cycles per second).
2. Rectification of the beat current.
3. Amplification at the beat radio frequency, preferably by a tuned amplifier.
4. Audio frequency modulation of the amplified current.
5. Rectification of the modulated current.

For reception of damped wave or radiophone signals, step 4 is omitted. It is shown that in this case the quality (characteristic tone) of the incoming signals is preserved.

DISCUSSION

A. S. Blatterman (by letter received December 17, 1919): Up to the present time it has been found very difficult to amplify radio signals having oscillation frequencies of the order of 1,000,000 cycles and practically impossible to do so when the frequency reaches 3,000,000 cycles or greater. The difficulties are attributable chiefly to capacity effects in the vacuum tubes as well as in the wiring, and also because it is a fairly difficult problem to build a really satisfactory coupling impedance or transformer to connect up the output of one tube with the input side of the tube next in series when the frequency is very high. Movements of the hands of the operator or of his body near the apparatus in such cases cause extremely minute changes in capacity which are, nevertheless, sufficient to cause changes in tuning that seriously reduce the received signals.

Moreover, it is seldom, if ever, that a radio receiver can be designed for a single frequency. Both at the extremely high frequencies just mentioned as well as for the lower frequencies corresponding to the long wave lengths, it is practically always necessary to arrange for reception over a more or less limited range of wave lengths and this requirement has also been a very serious factor in the design of all radio frequency amplifiers up to the present time. At radio frequencies it is possible, convenient and desirable to use tuned transformers for the couplings between successive stages; but because of the necessity for making the amplifier responsive over a large number of wave lengths the tuning of the transformers must be relatively broad. This involves the arbitrary introduction of resistance into the circuits and the loss in efficiency that results seriously reduces the overall amplification.

Major Armstrong has met the above difficulties in the way of radio frequency amplification by a method which in principle is as simple as it is highly ingenious, and, at least for the amplification of excessively short wave lengths, appears to be a satisfactory solution of the problem in hand. The principle can, as is stated by Major Armstrong, be applied to damped wave and continuous wave telegraphy and to telephony. For receiving continuous waves a second heterodyne, either self or separate, must be brought to act on the second detector or else some form of chopper must be used. For very short waves of the order of 50 meters, it is possible to make a self-heterodyne of the first tube and thus avoid the extra adjustments and apparatus required by a separate local oscillator.

In this case it is advisable to use as low a beat frequency as possible in order not to necessitate too much mistuning, and to design the amplifier circuits accordingly. The question, however, of selecting the proper super-audible beat frequency and the actions involved in the performance of these circuits are not as simple perhaps as Major Armstrong may have led some of us to believe. Upon closer inspection it is found that certain limitations must be imposed upon the design, especially in application to the reception of spark and telephone signals, and it appears likely that the system cannot be used to advantage at all radio frequencies.

The following paragraphs may be of particular interest in connection with the opinion held by some that the present amplifier will tend toward returning spark radio systems to the favor accorded them before the advantages of continuous waves were so fully appreciated and utilized.

GENERAL THEORETICAL CONSIDERATIONS

In the reception of *continuous waves* by the method under consideration the actions involved are relatively simple. The interference of the incoming signal oscillation with that produced locally results in a beat frequency which is almost truly sinusoidal and makes the design of the coupling transformers a very satisfactory proposition with the possibility of securing maximum amplification through sharp tuning and accurate resonance adjustments. In this case also, it is quite immaterial, as far as the operation of the amplifier is concerned, whether the super-audible beat frequency used is adjusted to something of the order of 100,000 or 200,000 cycles or whether it is set at a low value of say 15,000 cycles.

For receiving spark signals, however, and for telephony the situation is somewhat different. Special precautions must be taken in order to avoid distortion effects, and the selection of proper value of the super- audible beat frequency is important.

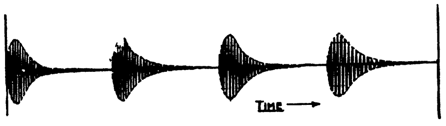

FIGURE 1

Figure 1 is supposed to represent trains of damped voltage oscillations such as are produced at the detector of a receiving circuit by a spark transmitter. The successive groups of oscillations recur at tonal frequencies, each group being the result of a discharge at the spark gap of the transmitter. The mathematical expression for such a train of oscillations may be written as follows:

$$[V + V_1 \sin(pt+\phi_1) + V_2 \sin(2pt+\phi_2) + V_3 \sin(3pt+\phi_3) + V_n \sin(npt+\phi_n)] \sin \omega_1 t \qquad (1)$$

wherein the bracketed expression is the equation of the envelope curve bounding the amplitude of the radio frequency oscillations, expressed in terms of a Fourier's series, and the last term, $sin\ w_1 t_1$ refers to the radio frequency oscillation of periodicity w_1 which is to be considered as an oscillation modulated at audible frequency according to the envelope curve just mentioned.

The envelope contains a fundamental frequency corresponding to p and all the harmonics $2p$, $3p$, $4p$,....np characteristic of the spark frequency and of the decrements of the transmitter and receiver. Thus, ordinarily the periodicity p would correspond to a 500- or 1000-cycle spark and the harmonics may run to the 10th or 20th before their amplitudes are small enough to make them negligible. V_1 V_2 V_3 .... V_n designate respectively the amplitudes of the fundamental and the various harmonics. $\phi_1, \phi_2 \ldots \phi_n$ and so on represent their phases.

The voltage produced by the local oscillator for heterodyning is

$$V' \cos (w_2 t + \theta) \qquad (2)$$

The total or resultant voltage acting on the first detector at every instant is therefore given by the sum of expressions (1) and (2). This can be written in the following form

$$\begin{aligned}
&V_1\left[\cos\frac{(\omega_1-\omega_2-p)\,t+(\phi_1-\theta)}{2}\cos\frac{(\omega_1+\omega_2-p)\,t+(\phi_1+\theta)}{2}\right.\\
&\qquad\left.-\sin\frac{(\omega_1-\omega_2+p)\,t+(\phi_1-\theta)}{2}\sin\frac{(\omega_1+\omega_2+p)\,t+(\phi_1+\theta)}{2}\right]\\
&+V_2\left[\cos\frac{(\omega_1-\omega_2-2p)t+(\phi_2-\theta)}{2}\cos\frac{(\omega_1+\omega_2-2p)t+(\phi_2+\theta)}{2}\right.\\
&\qquad\left.-\sin\frac{(\omega_1-\omega_2+2p)\,t+(\phi_2-\theta)}{2}\sin\frac{(\omega_1+\omega_2+2p)\,t+(\phi_2+\theta)}{2}\right]\\
&+V_3\left[\cos\frac{(\omega_1-\omega_2-3p)\,t+(\phi_3-\theta)}{2}\cos\frac{(\omega_1+\omega_2-3p)\,t+(\phi_3+\theta)}{2}\right.\\
&\qquad\left.-\sin\frac{(\omega_1-\omega_2+3p)\,t+(\phi_3-\theta)}{2}\sin\frac{(\omega_1+\omega_2+3p)\,t+(\phi_3+\theta)}{2}\right]\\
&+\\
&+V_n\left[\cos\frac{(\omega_1-\omega_2-np)t+(\phi_n-\theta)}{2}\cos\frac{(\omega_1+\omega_2-np)t+(\phi_n+\theta)}{2}\right.\\
&\qquad\left.-\sin\frac{(\omega_1-\omega_2+np)\,t+(\theta_n-\theta)}{2}\sin\frac{(\omega_1+\omega_2+np)t+(\phi_n+\theta)}{2}\right]\\
&+V\sin\omega_1 t \qquad\qquad (3)
\end{aligned}$$

In each of the bracketed terms four different frequencies appear, namely,

$$\frac{\omega_1-\omega_2-k\,p}{4\pi}$$

$$\frac{\omega_1-\omega_2+k\,p}{4\pi}$$

$$\frac{\omega_1+\omega_2-k\,p}{4\pi}$$

$$\frac{\omega_1+\omega_2+k\,p}{4\pi}$$

k having the different values 1, 2, 3, 4,...n corresponding to the 1st, 2nd, 3rd, 4th, or nth bracket involving the 1st, 2nd, 3rd, or nth harmonic.

The explicit values of these frequencies depend principally upon the values w_1 and w_2 of the incoming and local frequencies and also to an increasing extent upon the periodicities kp, of the audio harmonic spark frequencies, for the higher harmonics. Relatively, the four frequencies concerned may be of the same or very different orders of magnitude, and the two cases presented hereby involve important practical considerations in the design and use of the amplifier. The two different conditions may be treated separately under the headings (1) Short Wave Reception and (2) Long Wave Reception.

SHORT WAVE RECEPTION

The wave lengths to be considered here are of the order of 50 or 100 meters, or shorter. In this case w_1 and w_2 are both very large and of the four frequencies mentioned above the two involving the differences $w_1 - w_2$ are considerably smaller than the two comprising the sums $w_1 + w_2$. Thus, the two trigonometric products which appear in each of the bracketed terms of (3) indicate a radio frequency voltage of frequency

$$\frac{\omega_1+\omega_2\pm k\,p}{4\pi}$$

modulated by a considerably lower, though still super- audible, frequency, in the present amplifier, of value

$$\frac{\omega_1-\omega_2\pm k\,p}{4\pi}$$

The form of such a voltage wave for one of the trigonometric products is shown in Figure 2.

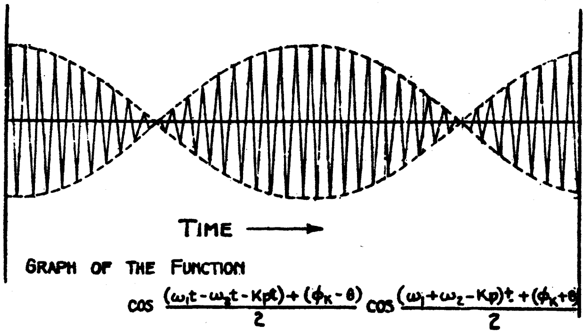

FIGURE 2

After rectification at the first detector tube the above frequencies are still essentially present and are impressed upon the amplifier proper. The frequencies

$$\frac{\omega_1-\omega_2\pm k\,p}{4\pi}$$

are the heterodyne beat frequencies produced by interference of the local and signal voltages. The transformers of the amplifier are designed for frequencies of their order of magnitude and are not, therefore, affected by the radio frequencies

$$\frac{\omega_1+\omega_2\pm k\,p}{4\pi}$$

No energy of these latter frequencies passes thru the amplifier. Neither does energy of the incoming signal (radio) frequency w_1 represented by the last term of (3), particularly if the transformers between stages of the amplifier are not broadly tuned. This is the normal way in which the amplifier works and is that described by Major Armstrong.

It is only the beat or difference frequencies

$$\frac{\omega_1-\omega_2-k\,p}{4\pi} \quad \text{and} \quad \frac{\omega_1-\omega_2+k\,p}{4\pi}$$

that have to be considered in designing the transformers and circuits. All of these frequencies lie in the neighborhood of the value

$$\frac{\omega_1-\omega_2}{4\pi}$$

which is the fundamental or basic beat frequency produced by the signal and local oscillations. They are greater and less than the value by the amounts

$$\pm\frac{p}{4\pi},\ \pm\frac{2\,p}{4\pi},\ \pm\frac{3\,p}{4\pi},\ \cdot\ \cdot\ \cdot\ \pm\frac{n\,p}{4\pi}$$

The transformers are fundamentally designed for the basic or mean frequency This can be adjusted by regulating the local oscillation *but its proper value is by no means immaterial.* It is limited in the lower ranges by the fact that it must be above audibility, and thus about 20,000 cycles is as low as is permissible. The limitations in the other direction are those usually encountered in amplification of extremely high frequencies and a value of 5 X 10^5 cycles is about as high as can be used effectively.

The transformers should be as sharply tuned as possible to permit the building up of high voltages and avoid losses in resistance. A second requirement is that there shall be no distortion in the tonal quality of the received signal as it passes thru the transformers.

This means that essentially all of the harmonics contained in the envelope curve of the arriving modulated oscillations must appear in the telephone current of the last detector. Thus, it is necessary to transmit equally thru the coupling transformers of the amplifier all of the frequencies.

$$\frac{\omega_1-\omega_2+k\,p}{4\pi} \quad \text{and} \quad \frac{\omega_1-\omega_2-k\,p}{4\pi}$$

and while designing the transformers for the basic frequency the tuning must be broad enough so that the response is practically uniform over all the frequencies up to on either side of the basic value. A spark signal may contain appreciable harmonics up to the 10th or 20th which in a 500 cycle transmission of the usual type would mean that the amplifier transformers at the receiver would have to pass side frequencies up to 10,000 or 20,000 cycles above and below the basic frequency on which the design is based.

Laboratory experience has shown that it is difficult to build high frequency transformers tuned flatly enough to pass frequencies more than about 40 percent above or below their best frequency. Even this value is accompanied by a marked loss of over-all efficiency because of the resistance effect that must be introduced to broaden the tuning. It is obviously impractable, therefore, to use transformers designed for a heterodyne frequency of 20,000 or 30,000 cycles, because a great many of the harmonic side frequencies that have to be transmitted to preserve the quality would be lost, and in order to get even a few of them the flat tuning required and the resistance inserted to secure it would mean low efficiency. It is much better in this case to work at a beat frequency of 100,000 cycles. The 10th harmonic in the spark frequency under consideration, that is: 10,000 cycles, is then only off tune by 10 per cent which allows fairly good efficiency to be realized in the transformers. A beat frequency of 200,000 cycles would be even better.

There is another circumstance which favors the use of high beat frequencies, at least for the reception of short wave lengths, and that is the small changes in either the signal or the local oscillator frequencies such as might be caused by movements of the operator's hand or body in the neighborhood of one of the circuits, cause a much smaller percentage change in the beat frequency when this is high than when it is low, and the apparatus thereby becomes more nearly immune to such variations. At longer wavelengths, however, conditions are altered somewhat and there is an upper limit to the usable beat frequency.

The beat frequency can be produced with the local frequency (w_2) either less or greater than the incoming frequency (w_1). It is usually best, with short waves, to make w_2 less than w_1, because it is more easily controlled and freer from variations of the type just mentioned.

LONG WAVE RECEPTION

In the reception of long wave lengths a condition arises in which the incoming signal frequency is of the same order of magnitude as the heterodyne frequency for which the transformers are designed. Such is the case, for instance, when receiving a wave length of 3,000 meters with an amplifier tuned to the beat frequency of 100,000 cycles. When this condition exists, the incoming frequency, $\omega_1/2\pi$, represented by the last term of (3), passes thru the amplifier together with all the heterodyne frequencies

$$\frac{\omega_1-\omega_2-kp}{4\pi} \quad \text{and} \quad \frac{\omega_1-\omega_2+kp}{4\pi}$$

and interfering with all of them in their different amplitudes and phases produces a conglomeration of resultants which will be heard in the telephones, after rectification at the last detector, as a badly distorted, mushy signal like that usually heard when receiving spark signals on an ordinary oscillating receiver. This will always happen if the incoming signal frequency passes thru the amplifier. In order to avoid the effect, therefore, it is necessary to design the amplifier for heterodyne frequencies that lie wholly outside the range of wave lengths to be received. It is easy to accomplish this, as will readily be seen, when short wave lengths are involved but when waves of one or several thousand meters are to be handled the proper selection of the value of the heterodyne frequency requires careful consideration.

As an example, consider the case of a receiver to function on all wave lengths from 1,000 meters to 5,000 meters; that is, 300,000 cycles to 60,000 cycles. In order to avoid distortion of the kind just mentioned on certain wave lengths this whole band of frequencies is at once eliminated from use as heterodyne frequencies in the amplifier, and the range ought to be extended at least 10,000 cycles beyond this at both ends because the spark signal may contain appreciable harmonics up to this value and certain of the side frequencies of the incoming oscillation might therefore get directly through the amplifier and produce distortion. In the case under consideration, therefore, the amplifier ought to be designed for a frequency either less than 50,000 cycles or greater than 310,000 cycles.

The disadvantages in using low heterodyne frequencies (on the 50,000 cycle end in this case) have been pointed out above in discussing the reception of short waves. Broad transformer tuning with comparatively low efficiency is required to avoid the other kind of distortion due to elimination or at least the reduction of the higher harmonics. But in addition to this there must be considered the fact that static is always more pronounced at long wave lengths and an ampifier designed for low frequencies might therefore be expected to be more affected by these disturbances than one using higher frequencies.

For these reasons it appears very desirable to design the amplifier transformers for a beat frequency of the order of 35,000 or 400,000 cycles, that is, about 750 meters, in the case under consideration.

If spark or telephone signals were to be received on extremely long wave lengths such, for instance, as 15,000 meters (20,000 cycles) there is another consideration that would come in to limit the upper value of heterodyne frequency that could be used. This may best be explained by reference to the formula (3) above. High heterodyne frequencies of the order of 500,000 cycles cannot be used in this case because the sum of the signal and local frequencies $(\omega_1+\omega_2\pm k\,p)/4\pi$ (carrier frequencies) would come thru almost as well as the difference or desired beat frequencies, namely, $(\omega_1-\omega_2\pm k\,p)/4\pi$ (modulating frequencies) and very bad distortion would result. To take the figures given, f_1 would be 20,000 cycles and f_2 520,000 cycles. Their sum would be 540,000 and their difference 500,000, a variation of less than 10 per cent and both therefore conceivably within the working range of an amplifier transformer.

The type of distortion discussed above which is caused by the passage of the incoming frequency directly thru the amplifier and which results in a mushy, harsh signal can be confined to a rather narrow range of wave lengths by making the tuning of the amplifier transformers sharp. But this cannot be carried to extremes or, as has already been explained, it will then not be possible to pass the side frequencies. These will, in telephone transmissions, probably not exceed 2,000 cycles either side of the basic frequency but in spark signals may run to 10,000 cycles or so in extreme cases.

SHARPNESS OF TRANSFORMER TUNING

In order to get an idea of the sharpness of tuning desirable in the transformers under different conditions the curves of Figure 3 are given showing the variation of secondary transformer potential as function of the ratio $f_2/fP-1P-$ that is the ratio of the frequency to which the transformer secondary is tuned to the varying impressed frequency.

Curve "a" is for a broadly tuned transformer of decrement 0.8; curve "b" represents sharper tuning with a decrement of 0.2. It will be seen that in the first case a frequency change of 10 per cent from the best value will cause a reduction in signal of about 5 per cent. In the second case, a difference in frequency from the best value of only 2 per cent causes the same change in signal.

If the 5 per cent reduction in potential for the side frequencies is assumed to be as much as is allowable in order to avoid distortion, and if it is further assumed that as sharp tuning as represented by the curve "b" with 0.2 decrement is to be usable and the harmonics or side frequencies to be passed are to run to 5,000 cycles then the basic heterodyne frequency for which the transformers must be set will have to be at least 250,000 cycles; and if 10,000 cycles either side of the basic frequency are to be passed the latter cannot be less than 500,000 cycles, which is about the upper practical limit. It turns out, therefore, that curve "b" corresponding to a decrement of 0.2 represents about as sharp tuning as can be used, and even then it is necessary to use the higher range of available heterodyne frequencies. It is to be noted that this tuning is by no means sharp as judged by the standards usually set for radio circuits.

With such tuning, frequencies 15 per cent greater and 30 per cent less than that to which the transformer is tuned are only reduced in amplitude by one half, and considerable energy within these frequencies would get directly thru the amplifier and produce the distortion just mentioned with harsh signal. In figures, it may be expected, if the amplifier were tuned to 3,000 meters, that mushy signals would be obtained for all waves between 3,900 and 2,550 meters.

If low heterodyne frequencies are to be employed then the tuning must be broader and the resonance curve "a" applies. Here, the allowable reduction of 5 per cent in response occurs for a change of about 10 per cent in frequency from the optimum value which means that the latter must be set for at least 50,000 cycles if a side frequency of 5,000 cycles is to get thru sufficiently to prevent distortion. With such broad tuning, however, even frequencies of half the value for which the transformers are designed get thru directly with very little loss and distortion with the mushy, harsh type of signal may be expected over a wide range of wave lengths.

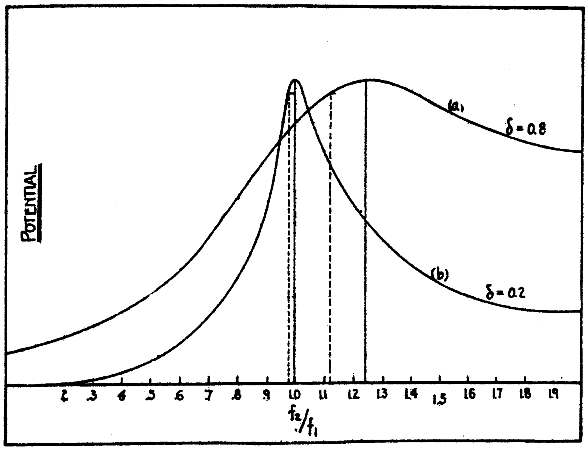

FIGURE 3

For purposes of design of the transformers it is possible from the above considerations to decide on the most suitable heterodyne frequency, the sharpness of tuning and the approximate decrement and to determine roughly the constants of the transformer from the relations

$$\delta = \frac{r_2}{2fL_2}$$

$$f = \frac{1}{2\pi\sqrt{L_2 C_2}}.$$

Still another point is involved here. In a pair of tuned coupled circuits such as must be used in the amplifier, the secondary and primary voltages are proportional inversely to the square root of the tuning capacities in the two circuits. That is

$$V_2 = \sigma V_1 \sqrt{\frac{C_1}{C_2}}$$

To get large secondary potentials, therefore, it is best to use small capacity and large inductance. Then, in order to keep the tuning or decrement to the desired value, the resistance must be increased, and these statements would hold without any qualification were the output of the vacuum tube not definitely affected by the transformer load in their plate circuits.

When tuned, the secondary of a transformer introduces an effective resistance into the primary equal to

$$\frac{M^2 \omega^2}{r_2}$$

so that changing the resistance of the secondary to secure the decrement required to pass the side frequencies affects the load on the tube. What is desired is to get as high a potential V_1 across the transformer primary as possible. This requires the load impedance to be high as compared with the internal tube impedance. Increasing r_2 therefore militates against this and the best results can only be secured by careful adjustment of all factors, coupling, resistance, and inductance to the frequency involved.

EFFECT OF TRANSMITTER DECREMENT AND ATMOSPHERICS

It appears that this type of amplifier functions most effectively on incoming waves of low decrement and that the atmospheric disturbances which are always highly damped or else actually dead beat may be eliminated to a very considerable degree.

Curve "b" of Figure 4 shows a train of oscillations in a receiving circuit such as would be produced by a spark transmitter operating at 3,000 meters wave length and decrement 0.12. The decrement of the receiver for this curve was taken as 0.08. Curve "a" is similar but drawn for an excitation of high decrement, 2.08, approximating a static disturbance of the same frequency as that which the receiver is tuned, that is, 3,000 meters. These curves can both be represented by equations of the form of equation (1) in which Fourier's series gives the equation of the envelope curve of the oscillations.

For the curve "b", that is, the case of smaller damping, the different amplitudes of the harmonics and of the constant term in the representative series are as follows:

$V = 7.86$
$V_1 = 12.23$
$V_2 = 5.92$
$V_3 = 3.72$
$V_4 = 2.09$
$V_5 = 1.56$
. . . . . .
$V_{10} = 0.40$

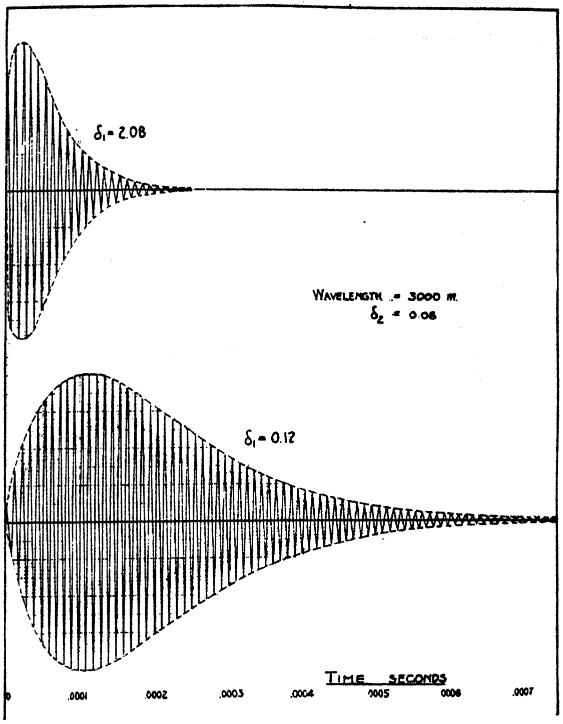

FIGURE 4

For curve "a" with high decrement the constants are:

$V = 23.6$
$V_1 = 38.4$
$V_2 = 24.0$
$V_3 = 19.2$
$V_4 = 14.3$
$V_5 = 12.2$
$V_{10} = 6.3$
. . . . . .
$V_{20} = 3.36$

The amplitudes of the fundamental and various harmonics in the two cases are plotted in Figure 5 assuming the fundamental to be 1,000 cycles as in the usual spark transmission.

It is seen that the amplitudes in the highly damped signal fall off much less rapidly than those of the more lightly damped signal. This means that in the former case a great deal of the total energy is contained in the harmonics, and if these are not passed thru the amplifier there will not only be distortion but loss in volume of signal as well. The use of a feebly damped spark transmission with an amplifier tuned just sharply enough to pass the principal harmonics or side frequencies produced therefore gives a system which largely eliminates static disturbances.

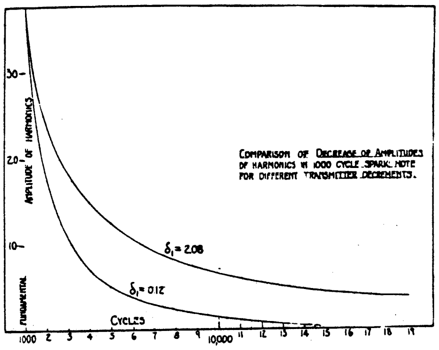

FIGURE 5

In this respect the present arrangement is more effective than the ordinary radio frequency amplifier. In the latter the presence of a strong signal oscillations at the detector, after having passed the amplifier, amplifies the static in the same way that a locally produced frequency would, so that when the receiver is tuned to the incoming signal very loud sounds are caused by the static. These diminish rapidly, however, as the receiver is detuned, because the signal energy then falls off and the ratio of this, the equivalent local oscillation amplitude, to the static amplitude being thus reduced there results a much greater than proportionate decrease in the endodyne amplification effect on the static, as has already been shown by Major Armstrong in another paper.[1] But in the new amplifier only the fundamental and the first few harmonics of the static impulse are amplified by these interactions and thus much of the energy of such disturbances is lost.

SUMMARY AND CONCLUSIONS

The above discussion has referred particularly to signals produced by spark transmitters, but the same general considerations are involved in telephone transmissions, except that in the latter the harmonic side frequencies to be considered will not generally exceed 2,000 cycles. The only point concerned in the case of sustained wave receptions is that involving the passage of the incoming frequency directly thru the amplifier and this should be avoided with sustained waves for the same reasons that have been given to cover spark transmission.

Several practical considerations have been omitted from the discussion. Of these, one of the most important is the difficulty that is encountered in placing the circuits of a radio frequency amplifier with their transformers in a box in such a way that sharp tuning may be obtained and yet not have the whole or part of the system go over into oscillation. This involves careful adjustment of the various couplings and the resistances of the circuits and the proportions and arrangements are usually different for every wave length. It is suggested that an improvement might be made in this type of amplifier over the circuits that have been drawn by Major Armstrong, in which he uses air core tuned transformers in all of the stages of the amplifier, by the use of a tuned air core transformer behind the first detector tube feeding the first stage of the amplifier and with the stages following this coupled by means of carefully designed iron core transformers. The latter keep down stray fields, and it has been found possible to build such transformers so as to get practically the maximum attainable amplification from the tube. By this arrangement the sharpness of tuning required in the amplifier is furnished by proper design of the first air core transformer, and the trouble experienced from coupling back, when several stages all tuned to the same frequency are employed, is reduced by the use of the iron core transformers which follow.

Two kinds of distortion are to be avoided. The first is caused by the passage of the incoming frequency directly thru the amplifier. The second is due to the more or less complete elimination of the harmonic side frequencies in passing thru the amplifier due to excessively sharp tuning. Thee type of amplifier in question is best suited to use on very short wave lengths, at least below 300 meters.

At long wave lengths it is difficult to avoid distortion of the two kinds mentioned, which, in the case of spark signals, results in a mushy, harsh note. Above 600 meters this type of distortion may be expected to occur over a band of wave lengths from 15 per cent to 30 per cent above and below that for which the amplifier is designed.

As regards an estimate of the allowable sharpness of tuning in different cases it would appear that this lies approximately between the limits set by decrements corresponding to 0.2, as about the sharpest tuning allowable, to about 0.8 for the broadest tuning. The latter would not be allowable except perhaps for the reception of very short waves. These figures apply only to the case where several tuned transformers are used in cascade in the amplifier. If the arrangement using one air core transformer and the balance iron core broadly tuned instruments as just described may be used, the tuning of the first air core transformer might be made considerably sharper than this, of the order usually found in ordinary receiving tuners.

In general, the basic frequency to be used in the design of the amplifier may be higher for long wave lengths than for short up to a certain point, the practical limit being in the neighborhood of 400,000 or 500,000 cycles for the reception of 6,000 meter spark signals. For very long waves the beat frequency cannot be made so high.

The analysis indicates that the amplifier can be made to be freer from interference from highly damped spark stations and static disturbances than the usual types.

There is one other point that has not been mentioned although I know it has already occurred to Major Armstrong himself. That is the question of the extent of the loss, if any, in effecting the change of incoming signal frequency to the value for which the amplifier is built. An experiment made [2] at Camp Alfred Vail in which the signal received on a simple non-regenerative tube was compared with that obtained by Major Armstrong's arrangement using a separate heterodyne, a rectifying tube for the super-audio note, and a detector tube, indicated that about equal signals were obtained by each method. Apparently, the heterodyne amplification in the second case just about makes up for the loss which accompanies the change in frequency.

Radio Laboratories,
Camp Alfred Vail, New Jersey
December 4, 1919

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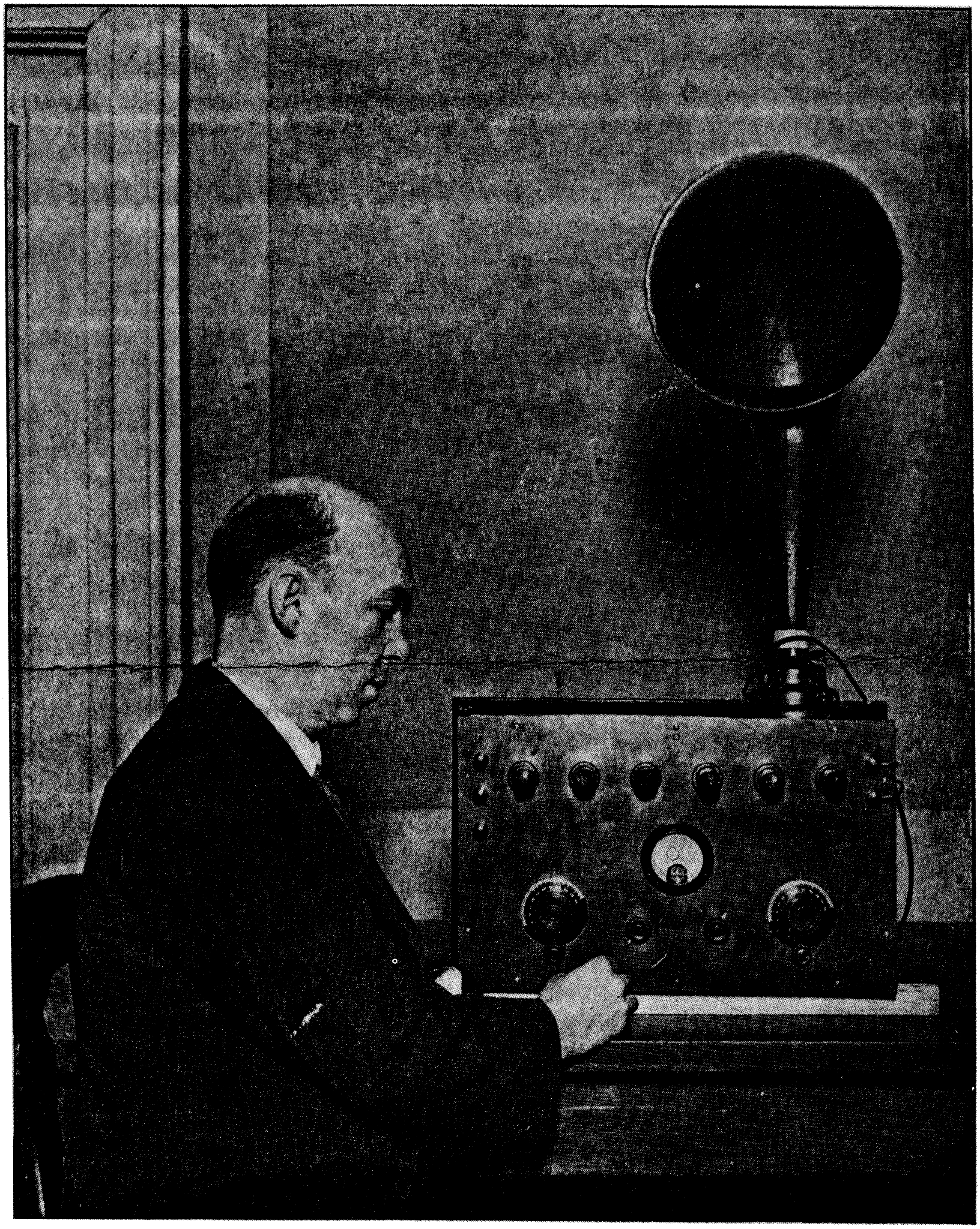
[1] E. H. Armstrong, *Proceedings of The Institute of Radio Engineers*, April, 1917.

[2] By Mr. M. C. Batsel, Assistant Radio Engineer, Signal Corps, United States Army.



EDWIN H. ARMSTRONG

And an early model of the six tube regenoflex second harmonic super-heterodyne—one of the greatest achievements ever made in broadcast receivers. This young inventor at one time studied under Professor J. H. Morecroft at Columbia University, New York City. Much of his present radio experimental work is being done at the Marcellus Hartley Laboratory at Columbia

The Story of the Super-Heterodyne

Its Origin, Development and Some Recent Improvements—A Radio Club of America Paper

By EDWIN H. ARMSTRONG

Marcellus Hartley Research Laboratory, Columbia University, New York

THE purpose of this paper is to describe the development of the super-heterodyne receiver from a war-time invention, primarily intended for the exceedingly important radio telegraphic direction finding service in the Signal Corps of the American Expeditionary Force, into a type of household broadcasting receiver, which, with our present vision, appears likely to become standard.

The invention of the super-heterodyne dates back to the early part of 1918. The full technical details of this system were made public in the fall of 1919. Since that time it has been widely used in experimental work and is responsible for many of the recent accomplishments in long-distance reception from broadcasting stations. While the superiority of its performance over all other forms of receivers was unquestioned, very many difficulties rendered it unsuitable for use by the general public and confined it to the hands of engineers and skilled amateurs. Years of concentrated effort from many different sources have produced improvements in vacuum tubes, in transformer construction, and in the circuits of the super-heterodyne itself, with the result that early in the month of April there has been made available for the general public, a super-heterodyne receiver which meets the requirements of household use.

Truth and Poetry—Plus Romance

No reader who makes a practice of neatly avoiding the "technical articles" should miss any of these fascinating lines of Edwin Armstrong's straightforward story of the development of the super-heterodyne, which is quite decidedly romantic in spite of the simple and direct way in which it is told.

This article tells how the second harmonic super-heterodyne was developed after the pressure of war-time necessity had caused the practical invention of the receiver. Mr. Armstrong has some pertinent remarks to make on radiation, reradiation, and the future of broadcast reception in general.

Here is an article that no one genuinely interested in radio should fail to read. It is an article we are proud to publish.—THE EDITOR.

It is a peculiar circumstance that this invention was a direct outgrowth of the failure of the vacuum tubes constructed in the United States to meet a very important problem confronting the American Expeditionary Force. This problem was the reception of extremely weak spark signals of frequencies varying from about 500,000 cycles to 3,000,000 cycles, with an absolute minimum of adjustments to enable rapid change of wavelength. The technical difficulties of this problem are now so well known that it is not necessary to consider them.

H. J. Round in England, and Latour in France, by some of the most brilliant technical radio work carried out during the war, had produced substantially aperiodic radio-frequency amplifiers covering the band from 500,000 to 1,200,000 cycles and though covering a much more limited band, amplifiers operating on 2,000,000 cycles had been constructed. These results had been accomplished by the use of vacuum tubes and transformers of a minimum capacity. As this apparatus was used in the highly important intelligence services, all information was carefully guarded. When the United States entered the war, the fact that it was necessary to produce extremely sensitive receivers for short wavelengths and that tube capacity would prove the bar to a straightforward solution of the problem was not known in this country. As a result, no attention was paid to the capacity in the type of vacuum tube which was adopted and while the tube met the

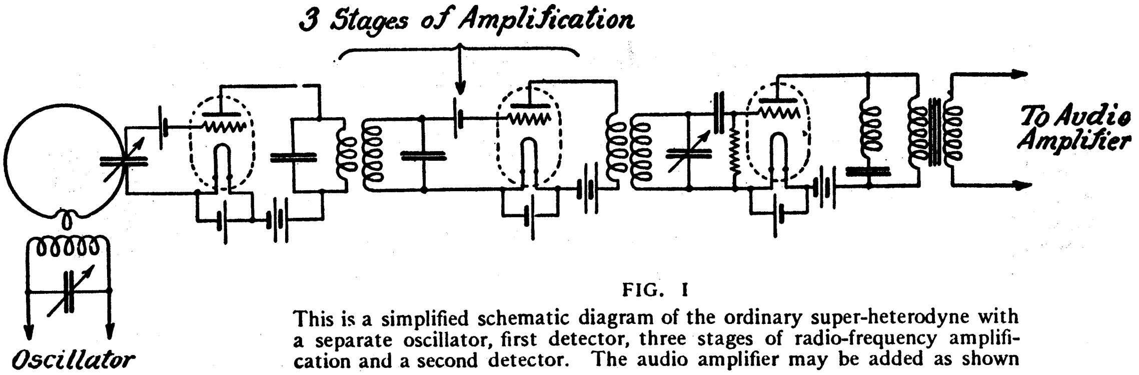


FIG. I

This is a simplified schematic diagram of the ordinary super-heterodyne with a separate oscillator, first detector, three stages of radio-frequency amplification and a second detector. The audio amplifier may be added as shown

requirements of the lower frequencies admirably, it was impossible to use it effectively for the frequencies of importance in the direction finding service.

HOW THE SUPER-HETERODYNE ORIGINATED

DURING the early part of 1918, through the courtesy and energy of General Ferrié and his staff, the American Expeditionary Force was supplied with apparatus of French manufacture. It was quite apparent, however, that this source of supply could not be a permanent one and a solution of the problem became essential. During the early part of 1917, I had made a careful study of the heterodyne phenomena and their effect on the efficiency of rectification. With these experiments freshly in mind, the idea occurred to me to solve the problem by selecting some frequency which could be handled by the tubes available, building an effective amplifier for that frequency, and then transforming the incoming high frequency to this readily amplifiable value by some converting means which had no low limit; preferably the heterodyne and rectification. The principles and advantages of this method were explained in a paper presented before this Institute and are now so well known that no further explanation is required here.

After much experimental work, an eight-tube set was constructed consisting of a rectifier tube, a separate heterodyne oscillator, three intermediate-frequency amplifiers, a second rectifier or detector, and two audio-frequency stages. The intermediate-frequency stages were coupled by tuned air-core transformers set for a frequency of about 100,000 cycles, with an adjustment for controlling the regeneration. The amplification of voltage measured at the input of the second detector with the amplifier just below the oscillating point, was about equivalent to a radio-frequency amplification of 500.[1] The arrangement of its circuits in Fig. 1 gave satisfactory results except that the inclusion of a regenerative control on the intermediate-frequency amplifier made skilled handling necessary, as the adjustment of the frequency of the oscillator changed the plate current of the detector tube and this, in turn, varied the resistance which that tube introduced into the amplifier system and upset the regenerative adjustment.

The Armistice ended development at this point, but in the fall of 1919, for the purpose of determining the results which could be obtained by pushing the super-heterodyne method of reception to the limit, a resistance-coupled intermediate-frequency amplifier consisting of five high mu tubes was constructed. The voltage amplification of these five stages was probably between 5,000 and 10,000 fold. While greater amplification could have been obtained, the sensitiveness of a set composed of a two-tube frequency converter, a five-tube intermediate-frequency amplifier, a detector, and one-stage of audio, was such that on a three-foot (one-meter) loop, the sole criterion of reception was simply whether the signal was stronger than the atmospheric disturbances.

PAUL GODLEY USED A SUPER-HETERODYNE TO COPY AMERICAN AMATEURS IN SCOTLAND

THE sensitiveness of the super-heterodyne was demonstrated during the winter of 1919–1920 when the spark signals from amateur stations on the West coast and telephone signals from destroyers in Southern waters

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[1] This amplification is based on the ratio of the voltage applied to the second detector to the voltage at the loop terminals. The intermediate frequency amplification is unknown.

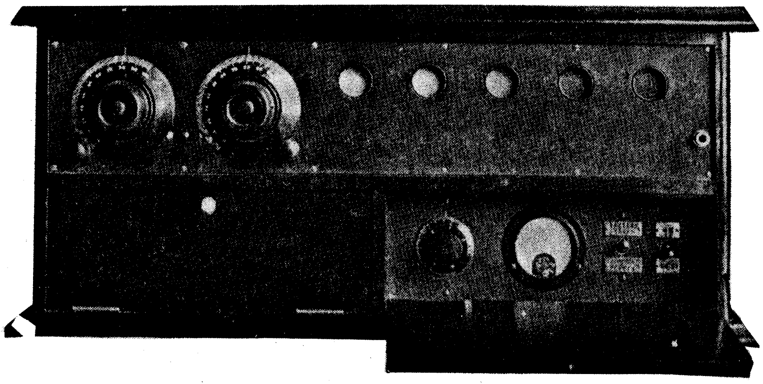

FIG. 2
This super-heterodyne is transformer-coupled and has been used by Major Armstrong in many demonstrations given under the auspices of the Radio Club of America

were received in the vicinity of New York on a three-foot (one-meter) loop. Probably the most striking demonstration of the capabilities of the method occurred in December, 1920, when Paul F. Godley, at Ardrossan, Scotland, received the signals of a large number of amateur stations located in the United States, many of them being spark stations. The super-heterodyne used by Godley consisted of a regenerative tube for the first rectifier, a separate oscillator, four stages of resistance-coupled intermediate-frequency amplification, a second rectifier, and two stages of audio. While it is difficult to state definitely the actual voltage amplification obtained, it appears to have been between 3,000 and 5,000 fold.[1]

With the coming of broadcasting and with the great increase in the number of stations and the consequent interference, the super-heterodyne began to take on a new importance —an importance which was based not on its superior sensitiveness nor on its selectivity, but on the great promise which the method offered in simplicity of operation. It was, and still is, the standard practice to furnish the public with receivers equipped with a variety of tuning adjustments for the purpose of amplifying the desired band of radio frequencies and excluding all others. As a matter of fact, many more adjustments are on receivers than should be used—more than could be placed in the hands of the average user. It would obviously be of the greatest importance if in some way these tuning adjustments could all be made in the laboratory by skilled engineers and sealed, leaving some relatively simple adjustment for the hands of the operator. The super-heterodyne offered the ideal solution. This solution lay in the construction of an intermediate-frequency amplifier which would amplify a given frequency and a band 5,000 cycles above and below it and which would cut off sharply on either side of this desired band. The adjustments necessary to accomplish this could all be made by skilled men, and the only operations left for the user would be the two adjustments necessary to change the incoming frequencies down to the band of the amplifier—adjustments which are not dependent on each other, which are of extreme simplicity, and which can be made equally well by the novice or the engineer. To determine just what could be accomplished along these lines, the writer, working in conjunction with Mr. Harry Houck constructed during the spring of 1922, a set designed for the maximum usable sensitiveness and selectivity.

THE FIRST MODEL

THE set-up consisted of one radio-frequency stage (non-tuned transformer) a rectifier tube, an oscillator tube (used as a separate heterodyne), a three-stage iron-core transform-

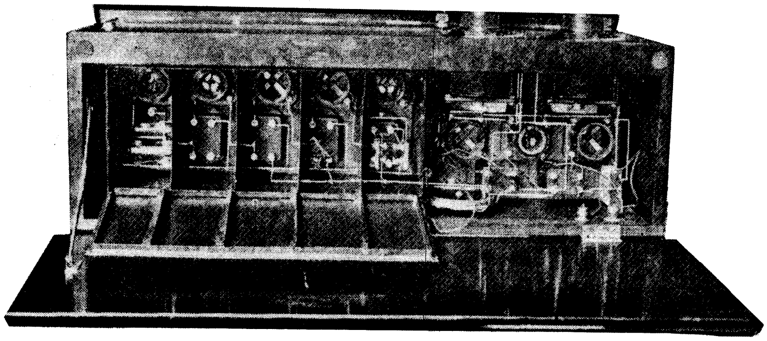

FIG. 3
This is the interior of the receiver pictured above

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[1] (Based on the standard previously described. This is without the second heterodyne which was used in receiving continuous waves.)

er-coupled intermediate-frequency amplifier designed to cover a band of 20,000 to 30,000 cycles, a second detector tube, and two stages of audio-frequency amplification. UV-201-A tubes were used. The set without the audio-frequency amplifiers is illustrated in Fig. 2 and Fig. 3. To prevent the intermediate-frequency amplifier from oscillating, each stage was shielded separately. The use of a radio-frequency stage ahead of the first detector possesses a number of advantages but the chief one is in eliminating the reaction between the loop circuit and the oscillator circuit. Experience with the original type had shown that when an oscillator of ordinary power was used, it was necessary to couple it rather closely with the loop circuit in order to insure a sufficiently strong heterodyning current. This close coupling affected the tuning of both circuits, an adjustment of one changing the setting of the other. To avoid this trouble and to produce a system wherein a station could always be tuned-in on exactly the same settings, a single stage of radio-frequency amplification (using a non-tuned transformer) was used, and the oscillator was coupled into this transformer. This arrangement eliminated the reaction, reduced the radiation to a minimum, and, in addition, removed the damping of the first rectifier from the loop circuit and improved its selectivity.

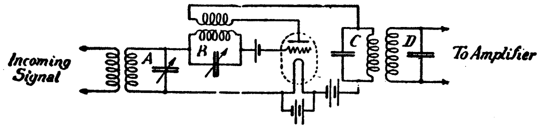


FIG. 5
The fundamental circuit of the second harmonic method of producing the oscillator frequency

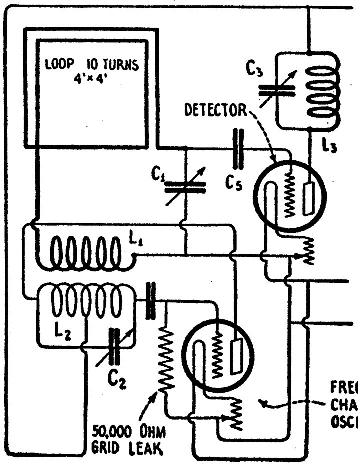


FIG. 4
The ordinary type of wave-changer for the super-heterodyne requires two tubes as shown here—the new method is shown in Fig. 5

The results obtained with this set were about as expected. On a three-foot (one-meter) loop, the factor determining the reception of a station was solely whether the signal strength was above the level of the atmospherics. The selectivity was such that stations which had never been heard before on account of blanketing by local stations, were received without a trace of interference. While the performance of the set was much superior to any other receiver, it was apparent that the cost of construction and maintenance was prohibitive. The single item of a ten-ampere filament current will give some idea of the size of the storage battery and auxiliary apparatus required.

With the coming of the low filament consumption, or dry battery type of tube, the possibilities of producing a super-heterodyne for household use were tremendously improved. The set of Fig. 3 was remodelled for the WD-11 tube and its sensitiveness was brought to about the same value as obtained with the storage battery tubes. This was a long step forward but still its cost was prohibitive.

WHY THE SECOND HARMONIC PRINCIPLE WAS DEVELOPED

IT HAD been apparent ever since the question of the application of the super-heterodyne to broadcasting had been considered, that there were too many tubes performing a single function which were quite capable of perform-

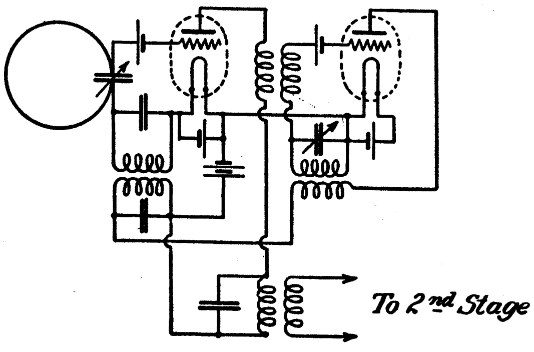


FIG. 6
This circuit makes it possible to reflex some of the intermediate amplifier tubes, using them for audio amplification as well. The result is more economical operation

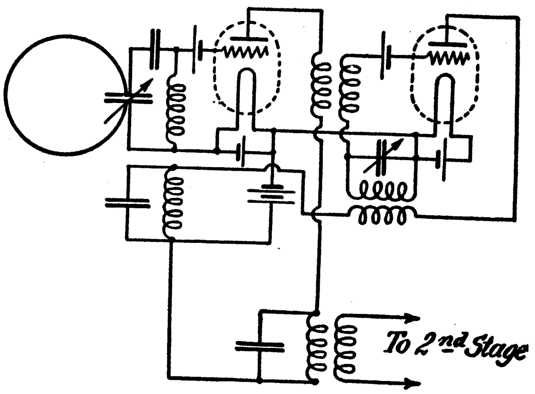
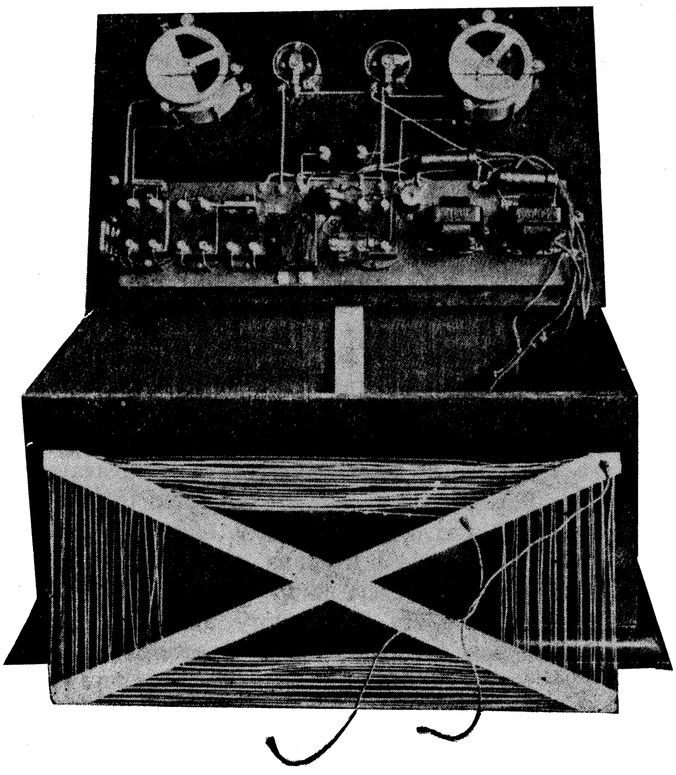


FIG. 7
A similar arrangement to that shown in Fig. 5 and explained in the text

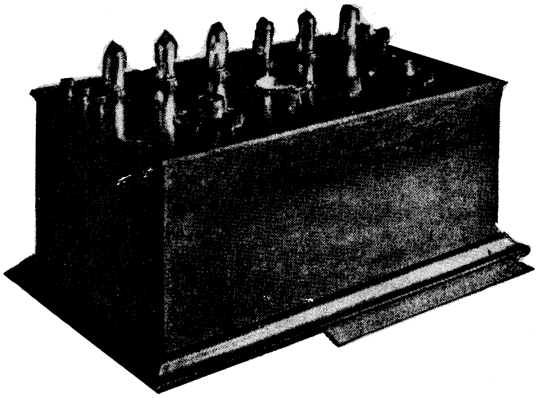
ing a double one. The most outstanding case is that of the separate heterodyne oscillator. In view of our knowledge of the self-heterodyne, it appears quite obvious to perform the first rectification by means of a self-heterodyne oscillator and thereby save a tube. As a matter of fact, this was one of the very first things tried in France, but, except for very short wavelengths, it was never very successful when a high intermediate frequency was necessary. The reason was this. If a single tuned oscillating circuit was used, the detuning to produce the proper beat caused a loss of signal strength which offset the gain of a tube. If two tuned circuits were used on the oscillator, one tuned to the signaling frequency and the other arranged to oscillate at the heterodyning frequency, then on account of the relatively small percentage difference in frequency a change in the tuning of one circuit changed the tuning of the other. The solution of this problem was made by Houck, who proposed an arrangement so simple and so effective that it completely solved the problem. Houck proposed to connect two tuned circuits to the oscillator, a simple circuit tuned to the frequency of the incoming signal and a regenerative circuit adjusted to oscillate at such a frequency that the second harmonic of this frequency beating with the incoming frequency produced the desired intermediate frequency. The general arrangement is illustrated by Fig. 5.

In this circuit A is tuned to the incoming signal, circuit B is tuned to one-half the incoming frequency plus or minus one-half the intermediate frequency, and the circuits C and D are both tuned to the intermediate frequency. The operation of the system is in line with ordinary self-heterodyne action. By reason of the asymetrical action of the tube, there are created in the circuits a variety of harmonics. The second harmonic combines to produce beats with the incoming signals of the desired intermediate frequency, the tube rectifies them to produce the desired intermediate frequency and, through C and D, the new frequency is supplied to the amplifier. On account of the fact that circuits A and B are tuned to frequencies differing by approximately 100 per cent., a change in the tuning of one has no appreciable effect on the tuning of the other. This arrangement solved the oscillator problem and, in addition, practically eliminated radiation.



This is the interior of the original receiver built on the second harmonic principle

The next step in the reduction of the number of tubes, was to make the radio-frequency amplifier perform the function of amplifying intermediate-frequency as well. This can be done with none of the difficulties inherent in audio-frequency amplification, as the very small amplitudes of voltage handled by the first tube precludes the possibility of the grid becoming positive with respect to the filament. The general arrangement of circuits for carrying this out is illustrated by Fig. 6. In this arrangement the signals received by the loop are amplified at radio-frequency by the first tube and applied to the grid of a second harmonic oscillator by means of an untuned radio-frequency transformer. The combined signaling and heterodyning currents are then rectified by the second tube producing a current of the intermediate-frequency which is applied to the grid of the first tube, amplified therein and passed on to the second stage of the intermediate-frequency amplifier. A more practical method of carrying out this idea is illustrated in Fig. 7. In this arrangement, a secondary of the first intermediate-frequency transformer is connected to the grid of the first tube and in parallel with the loop circuit. Otherwise, the arrangements of Figs. 6 and 7 are identical. The parallel type of circuit arrangement eliminates a variety of reactions which would give rise to oscillations of various frequencies and in addition, prevents the reception of long-wave signals by the intermediate-frequency amplifier. When this development had been completed, improvements in the design of the intermediate-frequency transformers made it possible to obtain with two stages all the amplification which could be used.



One of the early models of the six-tube receiver. The receivers now sold employ a similar circuit

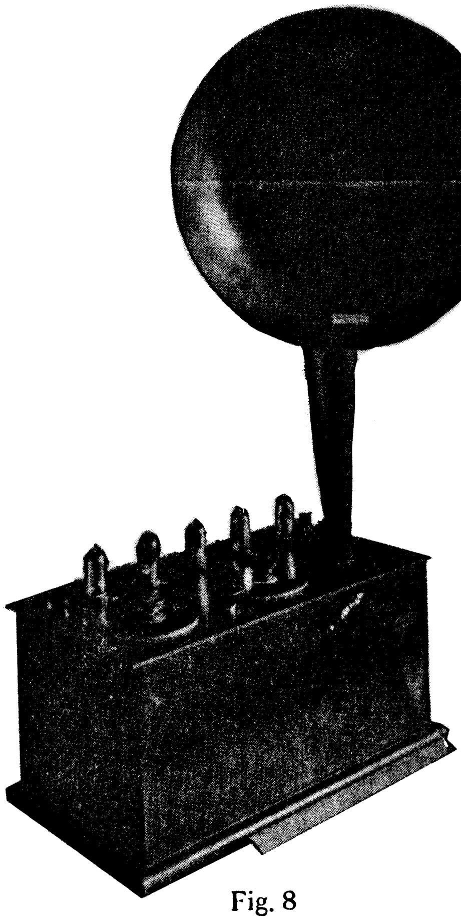


Fig. 8

In this five tube layout a loud speaker has been incorporated

On account of the high amplification, signals from local stations overload the second rectifier and introduce distortion. Control of the amount of intermediate-frequency amplification is essential. While there are numerous methods equally effective, the simplest one appears to be the control by means of the filament temperature of the second intermediate-frequency amplifier.[1]

The features just described were all incorporated in the receiver which is illustrated in Figs. 8 and 9. The set measured 16″ x 10″ x 10″ and was completely self-contained—the batteries, loop antenna, and speaker mechanism being enclosed in the box. The results were highly satisfactory and loud speaker signals (at night) in the vicinity of New York were obtained from stations in Chicago and Atlanta. It demonstrated that not only could a household receiver of the super-heterodyne

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[1] Although some form of potentiometer type of control of the voltage applied to the grid of one of the amplifier tubes would obviously be better, the simplicity of the filament control has many advantages in manufacture.

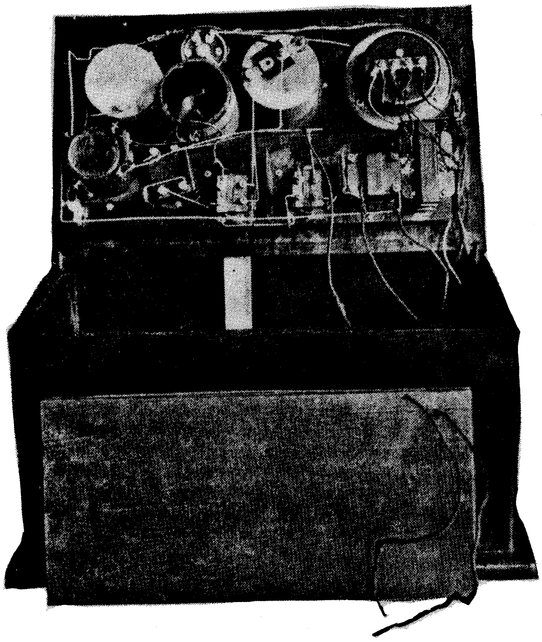

FIG. 9
Interior of the super-heterodyne portable with which an inexperienced woman heard 2LO during the tests run by Radio Broadcast and the *Wireless World* (London) last November

type be built, but that the first practical solution of the portable set was at hand.

FROM THE LABORATORY MODEL TO THE COMMERCIAL PRODUCT

IN THIS form, the capabilities of the set were brought to the attention of the Westinghouse Electric and Manufacturing Company and the Radio Corporation of America a little over a year ago. Its possibilities were instantly visualized by Mr. David Sarnoff, who immediately took steps to concentrate the resources of the research laboratories of the Radio Corporation of America, the Westinghouse Electric and Manufacturing Company and the General Electric Company on this new development. From that point on it passed into a new phase—that of placing an invention in a commercial form. In the limited time available, this was a most extraordinarily difficult proposition, and credit for its accomplishment is due to the untiring efforts on the part of the engineers of the above organizations. Many improvements and some radically new ideas of design have been introduced, but it is the privilege of those responsible for them to present these. In the final development of this receiver, an additional stage of audio-frequency amplification was added in order to insure operation within steel buildings, particularly those within the city limits where signals are relatively very weak compared to suburban locations. This makes a six-tube set but six tubes can be readily operated on dry batteries and the increase in sensitiveness is well worth the extra tube.

Some idea of the sensitiveness and the ease of operation of the set illustrated in Fig 9, may be gathered from an incident during the Radio Broadcast—*Wireless World* transatlantic broadcasting tests of November and December, 1923. On December 1st, two women, neither having any technical radio knowledge, received loud speaker signals from station 2LO, London, England. This was accomplished at Merrimac, Massachusetts, with the set and loop illustrated in Fig. 9 and perhaps constitutes a record for the first radiophone reception from Europe with a portable receiver. With the same set and a three-foot (one-meter) loop, loud speaker signals from broadcast stations on the Pacific Coast were received in the vicinity of New York on an average of three or four times a week. The sole criterion of reception was whether the signal strength was above the level of the atmospheric disturbances.

The type of super-heterodyne described herein is now available to the public in the two forms illustrated in Figs. 10 and 11. Each of

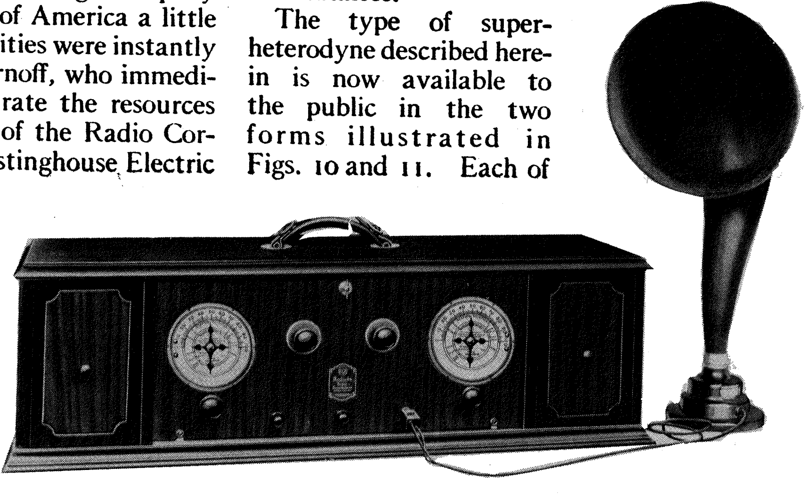

FIG. 10
The semi-portable six tube super-heterodyne now coming into great popularity. It is luxurious in appearance, simple to operate and produces excellent volume with marked clearness of tone

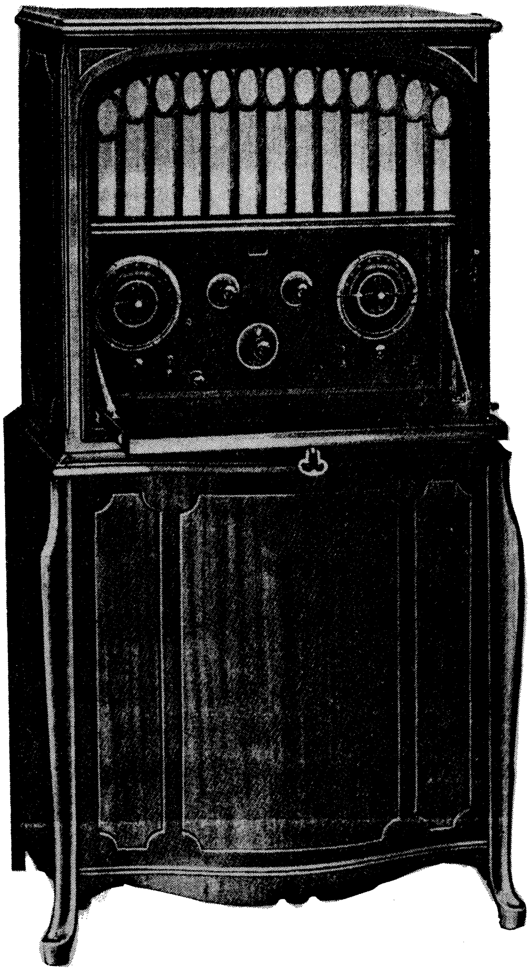

FIG. 11

The loud-speaker has been made a part of the receiver and a rotatable loop is provided in the case below. This receiver is one of the most luxurious ever placed on the market

these sets incorporate the arrangements herein described. Their sensitiveness is such that, with a two-foot loop and an unshielded location, the atmospheric disturbances are the criterion of reception. Here we reach a milestone in the development of broadcast receivers for no increase in the distance of reception can now be obtained by increase in the sensitiveness of the receiver. Unless the power of transmitting stations is increased we are about at the limit of the distance which can be covered. Future improvement of this receiver will lie along the line of increasing its selectivity and simplifying its construction. Aside from the development of the super-heterodyne but few recent radio receivers have improved in other than their mechanical arrangement and cabinet work.

APPENDIX

Some notes on the interaction between receiving sets.—Radiation—Coupling between antennas—Have broadcast stations enough power to go around?

PROBABLY the greatest outstanding problem in radio is the interaction between receiving sets. This interaction is due to several causes. The three main types may be classed under the heading "Radiation, Reradiation, and Coupling between Antennas."

At the present moment, much attention is focused upon the problem of radiating receivers. Much is being written about it under the misnomer "Reradiating receivers." Little has been written on the subject of reradiating receivers and still less about the problem resulting from the coupling between antennas. Doubtless this is due to the fact that the last two problems are at present masked by the first one. In my opinion, they are equally important, will cause increasing trouble and if radio proceeds along its present lines of development, will as seriously affect long distance reception as radiating receivers are affecting it at the present time.

To explain the above three types of interference, I will define each of them:—

RADIATION

THIS interference is produced by sets which, of their own volition, generate electrical oscillations of a frequency which is determined by the constants of their own circuits. The effect on neighboring receivers is the production of a beat note or whistle on wavelengths close to the frequency radiated by the oscillating receiver. This type of interference is commonly and improperly called "Reradiation." A radiating set may also produce interference by reradiation but this is a secondary matter and the primary cause of interference is radiation. The radiation is in the form of a continuous unmodulated wave.

RERADIATION

THIS type of interference results from an antenna picking up energy from an incoming wave and as the name implies, reradiating that energy into space. The reradiated energy is not a continuous unmodulated wave as in the previous case but a wave which is modulated substantially in accordance with the modulations of the received signals and which exists only as long as the received wave exists. This type of interference is most pronounced in the case of regenerative receivers which are set just below the point of oscillation. It causes trouble in near-by receivers in two ways. One is that the energy reradiated is not in the form in which it was originally transmitted from the sending station but has some of the characteristics of the receiving set superimposed upon it. The other is that the reradiated energy, particularly in the case of a large antenna with regeneration, boosts the signals in adjacent antennae, producing a fictitious signal strength in the other receivers which disappears when the large antenna is tuned to another station.

At present, receivers which regenerate in the antenna are responsible for most of the trouble. Elimination of regeneration in the antenna would aid the situation greatly. It would not, however, be a permanent solution of the problem. The elimination of regeneration in the antenna would merely reduce the area over which the effect of reradiation would be felt. If the number of antennae increase at the present rate, it will not be long before practically every antenna in a city will be within the reradiating range of a dozen others, each of which will make its influence felt. If regeneration is eliminated from all the antennae, then the question of whether the signal will be strengthened or weakened in any individual antenna on account of the proximity of the others, will depend largely upon their relative size, resistance and position. In general, a small antenna in the proximity of a large one will have its signals strengthened when the large antenna is tuned to the same wave, although this rule is not invariable.

COUPLING BETWEEN ANTENNAE

THIS type of interference is perhaps the most annoying of all. It occurs where two or more antennae are located so close together that each affects the tuning of the other. Where several antennae are associated together and produce this effect (for example, when they are all on the same roof) the difficulties of the operator in keeping his set in tune with a particular station can well be imagined.

At the present time in congested localities, all three of these types of interference occur and the solution of the radiation problem, while it is technically and economically possible of solution, will but serve to concentrate attention upon two other problems which are not technically capable of solution. In addition to these specific problems, we have in cities the much broader one of whether there is going to be enough energy to go around. It is perfectly apparent at the present time that the tuning of a large number of receivers in a congested area to the same signal results in a weakened signal for practically everybody. If every housetop were fitted with several antennae, the question arises as to how much energy the man in the center of the city would find left if everyone ahead of him had absorbed as much from the wave as possible by using as high and efficient an antenna as he could erect. The sole solution to this and all the other troubles is the use of an antenna of the loop type whose effect on near by receiving stations is negligible.

Of course, this necessitates more sensitive receivers with an increase in amplifying power commensurate with the relative receptive powers of an antenna versus a loop. At first sight, it might appear that the cost of this change would be prohibitive but with our present rate of development, I believe that it is going to be possible to build loop sets as sensitive as our present type antenna sets with but relatively little increase in cost. At the same time, the situation can be improved from another angle. The power of transmitting sets will gradually increase both because of the fact that there is no way to eliminate the effects of atmospheric disturbances, elevator induction, X-ray machines and all the other types of interference which exist in a large city except to ride over them with high power and because of the fact that from the program standpoint, it is economically better to concentrate talent at one point.

All these factors point to the elimination of the present type of antenna which will disappear in the same manner as the overhead telegraph, telephone, electric light and trolley wires have disappeared in the last twenty years.

THE SUPER-HETERODYNE

Its Origin, Development, and Some Recent Improvements

By **Edwin H. Armstrong**
Marcellus Hartley Research Laboratory,
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Presented before The Institute of Radio Engineers, New York, March 5, 1924
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The purpose of this paper is to describe the development of the super-heterodyne receiver from a wartime invention, primarily intended for exceedingly important radio telegraphic direction-finding service in the Signal Corps of the American Expeditionary Force, into a type of household broadcasting receiver, which, with our present vision, appears likely to become standard.

The invention of the super-heterodyne dates back to the early part of 1918. The full technical details of this system were made public in the Fall of 1919.[1] Since that time it has been widely used in experimental work and is responsible for many recent accomplishments in long distance reception from broadcasting stations. While the superiority of performance over all other forms of receivers was unquestioned, very many difficulties rendered it unsuitable for use by the general public and confined it to the hands of engineers and skilled amateurs.

Years of concentrated effort from many sources have produced improvements in vacuum tubes, in transformer construction, and in the circuits of the super-heterodyne itself, with the result that, at the beginning of the present month, there has been made available for the general public a super-heterodyne receiver which meets the requirements of household use. It is a peculiar circumstance that this invention was a direct outgrowth of some experimental work undertaken to meet a very important problem confronting the American Expeditionary Force. This problem was the reception of extremely weak spark signals of frequencies varying from about 500,000 cycles to 3,000,000 cycles, with an absolute minimum of adjustments to enable rapid change of wave length.

The technical difficulties of this problem are now so well known that it was not necessary to consider them.

Round in England and Latour in France, by some of the most brilliant technical radio work of the war, succeeded in producing radio frequency amplifiers covering the band from 500,000 to 1,000,000 cycles and though covering a much more limited band, amplifiers operating on 2,000,000 cycles had been constructed. These results had been accomplished by the use of vacuum tubes and transformers of a minimum capacity. As this apparatus was used in the highly important intelligence services, all information was carefully guarded.

When the United States entered the war, the facts that it was necessary to produce sensitive receivers for short wave lengths and that tube capacity would prove the bar to a straightforward solution of the problem were not known in this country. As a result, no attention was paid to the capacity in the type of vacuum tube which was adopted, and while the tube met the requirements of lower frequencies admirably, it was impossible to use it effectively for the frequencies of importance in the direction-finding service.

During the early part of 1918, through the courtesy and energy of General Ferriè and his staff, the American Expeditionary Force was supplied with apparatus of French manufacture. It was quite apparent, however, that this source of supply could not be a permanent one, and a solution of the problem became essential.

During the early part of 1917, I had made a careful study of the heterodyne phenomena and their effect on the efficiency of amplification.

With this work freshly in mind, the idea occurred to me to solve the problem by selecting some frequency which could be handled with the tubes available, building an effective amplifier for that frequency, and then transforming the incoming high frequency to this readily amplifiable value by some converting means which had no low limit; preferably the heterodyne and rectification. The principles and advantage of this method were explained in a paper presented before this Institute[3] and are now so well known that no further explanation is required here.

After much experimental work, an eight-tube set was constructed consisting of a rectifier tube, a separate heterodyne oscillator, three intermediate frequency amplifiers, a second rectifier or detector, and two audio frequency stages. The intermediate frequency stages were coupled by tuned air-core transformers set for a frequency of about 100,000 cycles, with an adjustment for controlling the regeneration. The amplification of voltage measured at the input of the second detector with the amplifier just below the oscillating point, was about equivalent to a radio frequency amplification of 500.[4]

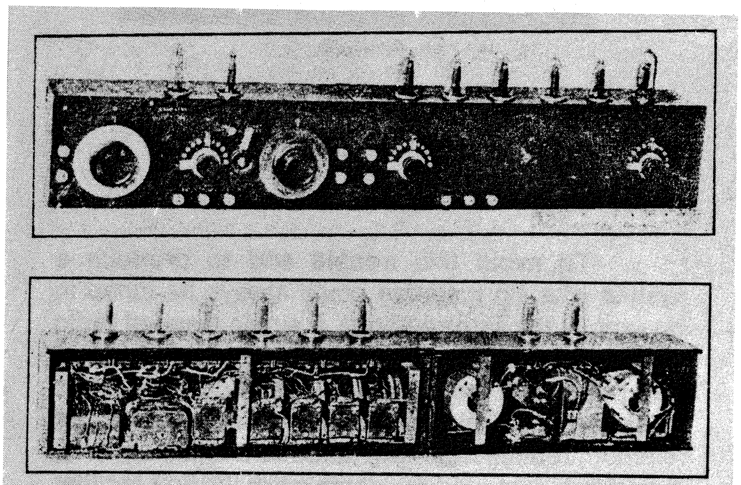


FIGURE 1

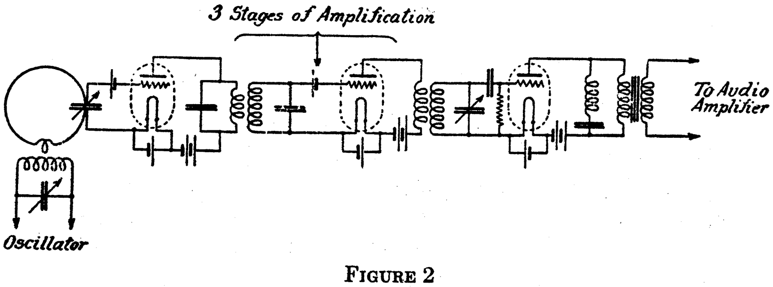


FIGURE 2

The set is illustrated in Figure 1 and the arrangement of its circuit in Figure 2. It gave satisfactory results except that the inclusion of a regenerative control on the intermediate frequency amplifier made skilled handling necessary, as the adjustment of the frequency of the oscillator changed the plate current of the detector tube and this, in turn, varied the resistance which that tube introduced into the amplifier system and upset the regenerative adjustment.

The Armistice ended development at this point, but in the fall of 1919, for the purpose of determining the results which could be obtained by pushing the super-heterodyne method of reception to the limit, a resistance-coupled intermediate frequency amplifier consisting of five high-mu (amplification factor) tubes was constructed. The voltage amplification of these five stages was probably between 5,000- and 10,000-fold. While greater amplification could have been obtained, the sensitiveness of a set composed of a two-tube frequency converter, a five-tube intermediate frequency amplifier, a detector, and one-stage of audio was such that on a three-foot (one-meter) loop, the sole criterion of reception was simply whether the signal was stronger than the atmospheric disturbances.

The sensitiveness of the super-heterodyne was demonstrated during the winter of 1919-1920 when the spark signals from amateur stations on the West coast and telephone signals from destroyers in southern waters were received in the vicinity of New York on a three-foot (one-meter) loop. Probably the most striking demonstration of the capabilities of the method occurred in December, 1920, when Paul F. Godley, at Ardrosson, Scotland, received the signals of a large number of amateur stations located in the United States, many of them being spark stations. The super-heterodyne used by Godley consisted of a regenerative tube for the rectifier, a separate oscillator, four stages of resisostance-coupled intermediate frequency amplification, a second rectifier, and two stages of audio. While it is difficult to state definitely the actual voltage amplification obtained, it appears to have been between 3,000- and 5,000-fold.

With the coming of the broadcasting art, and with the great increase in the number of stations and the consequential interference, the super-heterodyne began to take on new importance -- an importance which was based not on its superior sensitiveness nor on its selectivity, but on the great promise which the method offered in simplicity of operation. It was, and still is, the standard practice to furnish the public with receivers equipped with a variety of tuning adjustments for the purpose of amplifying the desired band of radio frequencies and excluding all others.

As a matter of fact, many more adjustments than are on receivers should be used -- more than could be placed in the hands of the average user. It would obviously be of the greatest importance if in some way these tuning adjustments could be made in the laboratory by skilled engineers and sealed, leaving some relatively simple adjustments for the hands of the operator. The super-heterodyne offered the ideal solution.

This solution lay in the construction of an intermediate frequency amplifier which would amplify a given frequency band and a band 5,000 cycles above and below it and which would cut off sharply on either side of the desired band. The adjustments necessary to accomplish this could be made by skilled men, and the only operations left for the user would be the two adjustments necessary to change the incoming frequency down to the band of the amplifier -- adjustments which are not dependent on each other, which are of extreme simplicity, and which can be made equally well by the novice or the engineer.

To determine just what could be accomplished along these lines, the writer, working in conjunction with Mr. Harry Houck, constructed during the Spring of 1922, a set designed for the maximum usable sensitiveness and selectivity. The set-up consisted of one radio frequency stage (non-tuned transformer), a rectifier tube, an oscillator tube (used as a separate heterodyne), a three-stage iron-core transformer-coupled intermediate frequency amplifier designed to cover a band of 20,000 to 30,000 cycles, a second detector tube, and two stages of audio frequency amplification. UV-201 tubes were used. The set without the audio frequency amplifier is illustrated in Figure 3 and Figure 4.

To prevent the intermediate frequency amplifier from oscillating, each stage was shielded separately. The use of a radio frequency stage ahead of the first detector possesses a number of advantages, but the chief one is in eliminating the reaction time between the loop circuit and the oscillator circuit. Experience with the original type had shown that when an oscillator of ordinary power was used, it was necessary to couple it rather closely with the loop circuit in order to insure a sufficiently strong heterodyne current. This close coupling affected the tuning of both circuits, an adjustment of one changing the setting of the other.

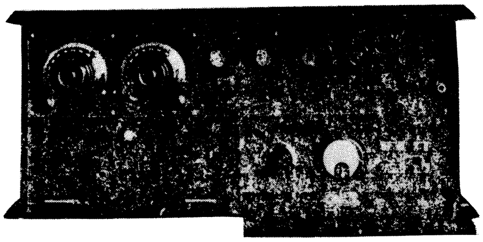


FIGURE 3

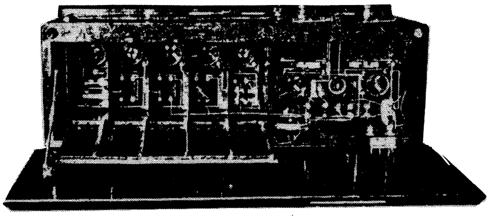


FIGURE 4

To avoid this trouble and to produce a system wherein a station could always be tuned in on exactly the same settings, a single stage of radio frequency amplification (non-tuned transformer) was used, and the oscillator was coupled into this transformer. This arrangement eliminated the reaction, reduced the radi- ation to a minimum and, in addition, removed the damping of the first rectifier from the loop circuit and improved its selectivity.

The results obtained with this set were about as expected. On a three-foot (one-meter) loop, the factor determining the reception of a station was solely whether the signal strength was above the level of the atmospherics. The selectivity was such that stations which had never been heard before on account of blanketing by local stations, were received without a trace of interference. While the performance of the set was much superior to any other receiver, it was apparent that the cost of construction and maintenance was prohibitive. The single item of a ten ampere filament current will give some idea of the size of the storage battery and auxiliary apparatus required.

With the coming of the low filament consumption, or dry battery type of tube, the possibilities of producing a super-heterodyne for household use were tremendous- ly improved. The set of Figure 3 was remodeled for the WD-11 tube, and its sensitiveness was brought to about the same value as obtained with the storage battery tubes. This was a long step forward, but still the cost was prohibitive.

It had been apparent ever since the question of the application of the super-heterodyne to broadcasting had been considered, that there were too many tubes performing a single function which were quite capable of performing a double one. The most outstanding case is that of the separate heterodyne oscillator. In view of our knowledge of self-heterodyne, it appears quite obvious to perform the first rectification by means of a self-heterodyne oscillator and thereby save a tube.

As a matter of fact, this was one of the very first things tried in France but, except for very short wave lengths, it was never very successful when a high inter- mediate frequency was necessary. The reason was this: If a single tuned oscillating circuit was used, the mistuning to produce the proper beat caused a loss of signal strength which offset the gain of the tube. If two tuned circuits were used on the oscillator, one tuned to the signaling frequency and the other arranged to oscillate at the heterodyne frequency, then on account of the relatively small percentage difference in frequency a change in the tuning of one circuit changed the tuning of the other.

The solution of this problem was made by Houck, who proposed an arrangement so simple and so effective that it completely solved the problem. Houck proposed to connect two tuned circuits to the oscillator, a simple circuit to the frequency of the in- coming signal and a regenerative circuit adjusted to oscillate at such a frequency that the second harmonic of this frequency beating with the incoming frequency produced the desired intermediate frequency. The general arrangement is illustrated in Figure 5.

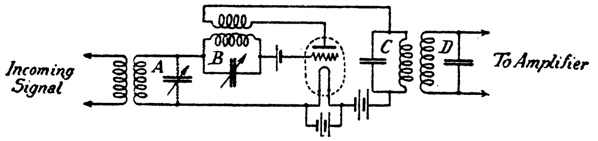


FIGURE 5

In the diagrammatic illustration, circuit *A* is tuned to the incoming signal, circuit *B* is tuned to one-half the incoming frequency plus or minus one-half the inter- mediate frequency, and circuits *C* and *D* are both tuned to the intermediate frequency. The operation of the system is in line with ordinary self-heterodyne action. By reason of the asymmetrical action of the tube, there are created in the circuits a variety of harmonics. The second harmonic combines to produce beats with the incoming signals of the desired inter- mediate frequency, the tube rectifies them to produce the desired intermediate frequency and, thou *C* and *D*, the new frequency is supplied to the amplifier. On account of the fact that circuits *A* and *B* are tuned to frequencies differing by approximately 100 percent, a change in the tuning of one has no appreciable effect on the tuning of the other. This arrangement solved the oscillator problem and, in addition, practically eliminated radiation.

The next step in the reduction of the number of tubes was to make the radio frequency amplifier perform the function of amplifying intermediate frequency as well. This can be done with none of the difficulties inherent in audio frequency amplification, as the very small amplitude of the voltages handled by the first tube preclude the possibility of the grid becoming positive with respect to the filament. The general arrangement of circuits for carrying out this is illustrated in Figure 6.

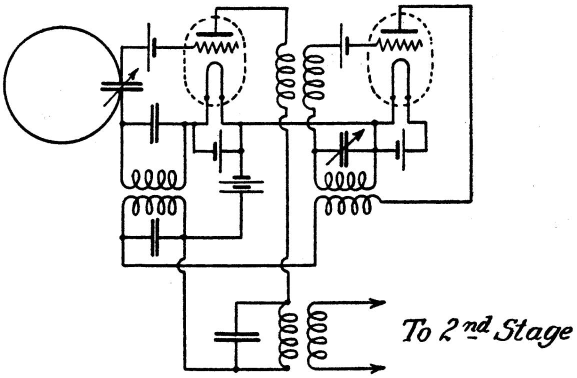


FIGURE 6

In this arrangement the signals received by the loop are amplified at radio frequency by the first tube and applied to the grid of a second harmonic oscillator by means of an untuned radio frequency transformer. The combined signaling and heterodyning currents are then rectified by the second tube, producing a current of the intermediate frequency which is applied to the grid of the first tube, amplified therein, and passed on to the second stage of the intermediate amplifier. A more practical method of carrying out this idea is illustrated in Figure 7.

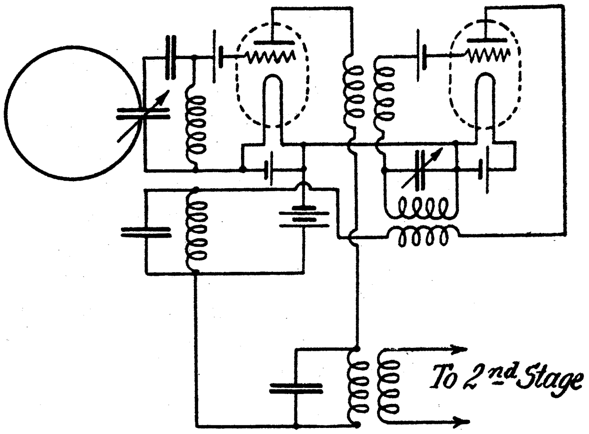


Figure 7

In this arrangement, a secondary of the first intermediate frequency transformer is connected to the grid of the first tube and in parallel with the loop circuit. Otherwise, the arrangement of Figures 6 and 7 are identical. The parallel type of circuit arrangement eliminates a variety of reactions which would give rise to oscillations of various frequencies and in addition, prevents the reception of long wave signals by the intermediate frequency amplifier. When this development had been completed, improvements in the design of the intermediate frequency transformers made it possible to obtain with two stages all the amplification which could be used.

On account of the high amplification, signals from local stations overload the second rectifier and introduce distortion. Control of the amount of intermediate frequency amplification is essential. While there are numerous methods equally effective, the simplest one appears to be the control by means of the filament temperature of the second intermediate frequency amplifier. [6]

The features just described were all incorporated in the receiver, which is illustrated in Figures 8 and 9. The set measured 18 by 10 by 10 inches (45.6 by 25.4 by 25.4 cm.) and was completely self-contained -- the batteries, loop antenna, and speaker mechanism being enclosed in the box. The results were highly satisfactory, and loud speaker signals (at night) in the vicinity of New York were obtained from stations in Chicago and Atlanta. It demonstrated that not only could a household receiver of the super-heterodyne type be built, but that the first practical solution of the portable set was at hand.

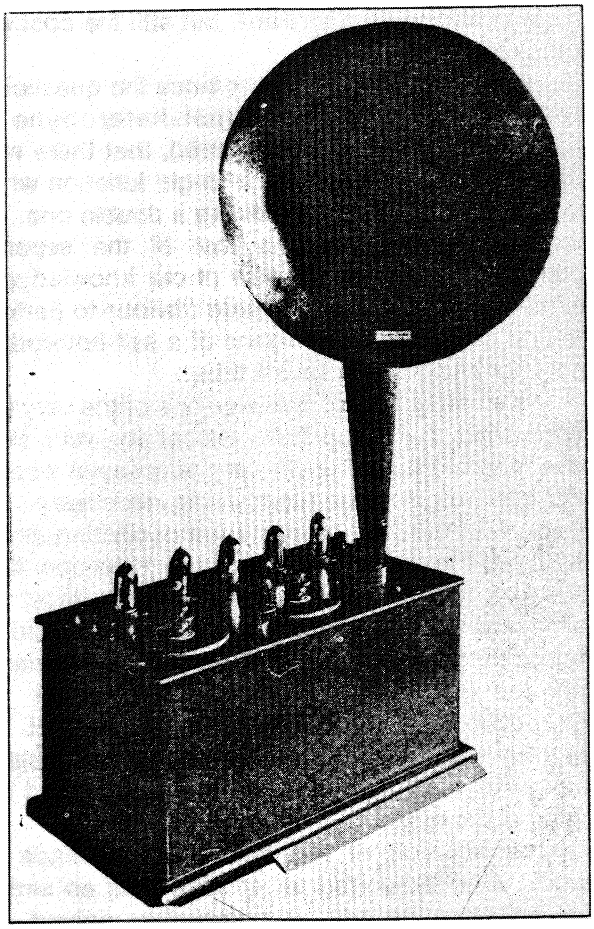


Figure 8

In this form, the capabilities of the set were brought to the attention of the Westinghouse Electric and Manufacturing Company and the Radio Corporation of America a little over a year ago. Its possibilities were instantly visualized by Mr. David Sarnoff, who immediately took steps to concentrate the resources of the research laboratories of the Radio Corporation of America, the Westinghouse Electric and Manufacturing Company, and the General Electric Company on this new development. From that point on it passed into a new phase -- that of placing an invention in a commercial form.

In the limited time available, this was a most extra-ordinarily difficult proposition, and credit for its accomplishment is due to the untiring efforts on the part of the engineers of the above organizations. Many improvements and some radically new ideas of design have been introduced but it is the privilege of those responsible for them to present these. In the final development, an additional stage of audio frequency amplification was added in order to insure operations within steel buildings, particularly those within the city limits where signals are relatively very weak compared to suburban locations. This makes a six-tube set, but six tubes can be readily operated on dry batteries and the increase in sensitiveness is well worth the extra tube.

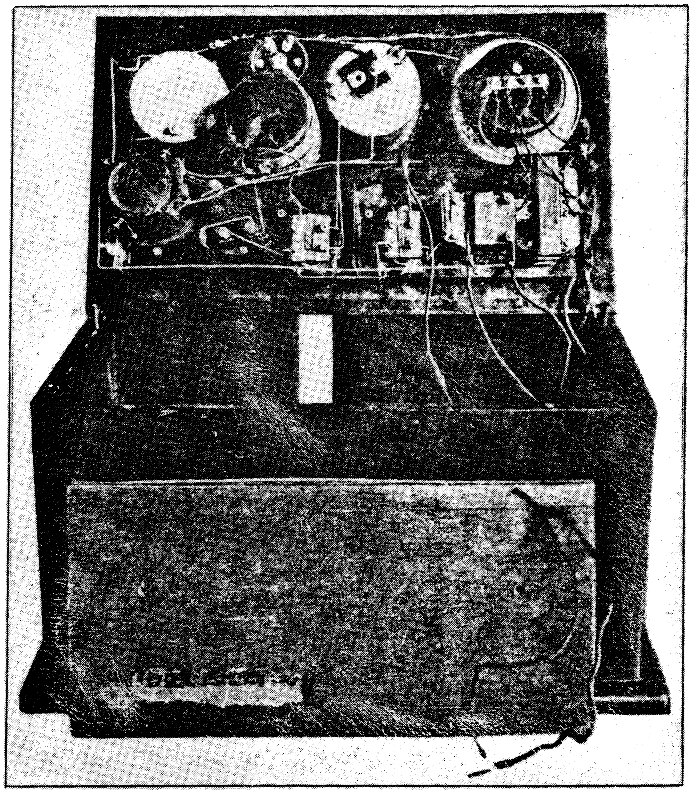


FIGURE 9

Some idea of the sensitiveness and the ease of operation of the set illustrated in Figures 10 and 11 may be gathered from an incident during the Transatlantic broadcasting tests of November and December, 1923. On December 1st, two ladies, neither having any technical radio knowledge, received loud speaker signals from station 2LO, London, England. This was accomplished at Merrimac, Massachusets, with the set and loop illustrated in Figures 10 and 11 and probably constitutes a record for the first radio-phone

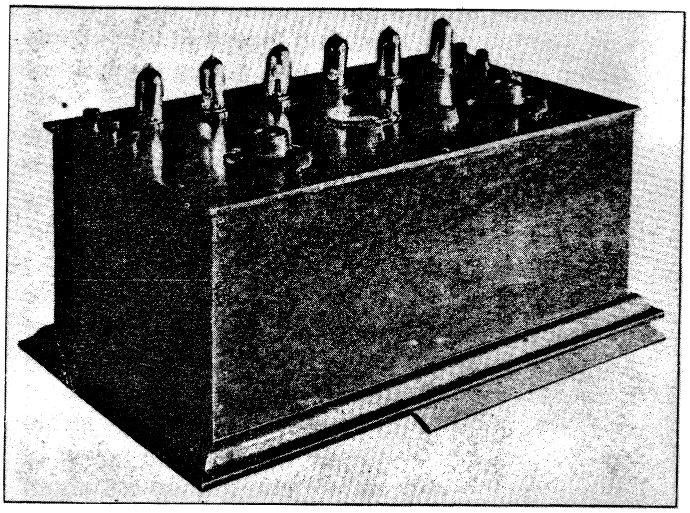


FIGURE 10

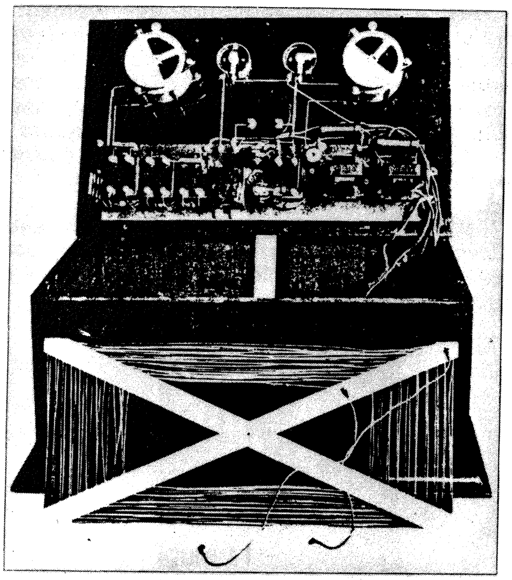


FIGURE 11

reception from Europe with a portable receiver.

With the same set and a three-foot (one meter) loop, loud speaker signals from broadcast stations on the Pacific Coast were received in the vicinity of New York on an average of three or four times a week. The factor determining reception was simply whether the signal strength was above the level of the atmospheric disturbances.

The type of super-heterodyne described is now available to the public in the two forms illustrated in Figures 12 and 13. Each of these sets incorporates the arrangements herein described. Their sensitiveness is such that, with a two-foot (61 cm.) loop and an unshielded location, the atmospheric disturbances are the criterion of reception. Here we reach a milestone in the development of broadcast receivers, for no increase in the distance of reception can now be obtained by increase in the sensitiveness of the receiver. Unless the power of the transmitting stations is increased we are about at the limit of the distance which can be covered. Future improvement of this receiver will lie along the line of selectivity and simplifying the construction.

SUMMARY:

This paper describes the development of the super-heterodyne receiver from a wartime invention into a commercial form of broadcast receiver apparatus now available to the general public. The success of the development is due to the low filament consumption vacuum tube and to the reduction in the number of tubes required by self-heterodyning, reflexing, and improvements in transformer design.

Instances are cited of transatlantic and transcontinental reception of broadcast stations by completely portable sets constructed in accordance with the methods described.

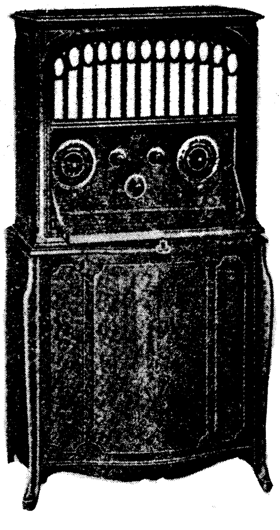


FIGURE 12

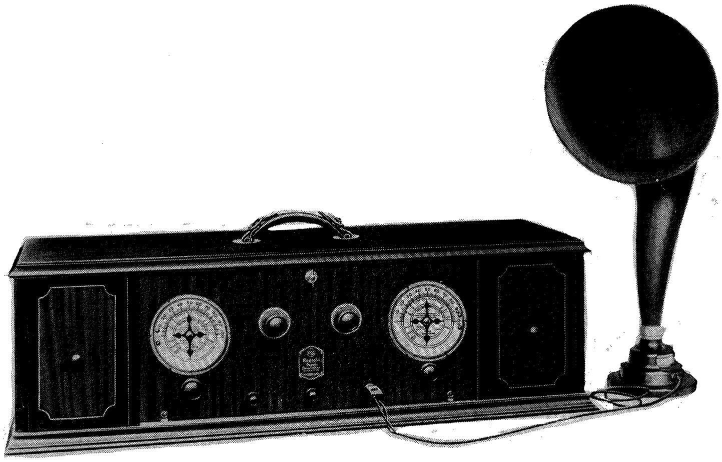


FIGURE 13

FOOTNOTES

[1] *Proceedings of The Institute of Radio Engineers,* February, 1921. Presented December 3, 1919.

[2] *Proceedings of The Institute of Radio Engineers,* April 1917. Presented October 4, 1916.

[3] This amplification is based on the ratio of the voltage applied to the second detector to the voltage at the loop terminals. The intermediate frequency amplification is unknown.

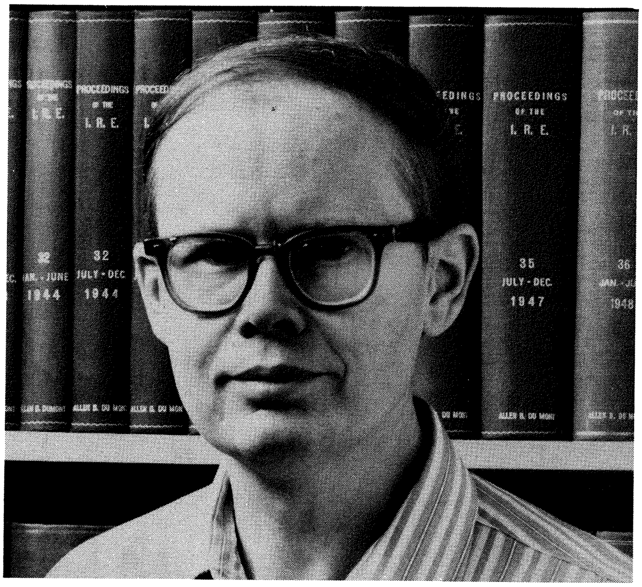
[4] *Proceedings of The Institute of Radio Engineers,* February, 1921. Presented December 3, 1919.

[5] Based on standard previously described. This is without the second heterodyne which was used in receiving continuous waves.

[6] Although some form of potentiometer type of control of the voltage (a.c. applied to the grid of one of the amplifier tubes would obviously be better) the simplicity of the filament control has many advantages in manufacture.

WHO INVENTED THE SUPERHETERODYNE ?

by **Alan S. Douglas (F)**



Of Armstrong's four principal inventions -- regeneration, superregeneration, the superheterodyne, and frequency modulation -- the superheterodyne has always seemed one of the least controversial. "Everyone" knows that Armstrong invented it. He devised it during World War I, patented it shortly afterward, sold his patent to Westinghouse who cross-licensed RCA and the radio industry, and that was that. Some Frenchman named Lèvy claimed he was first, but whoever heard of *him* ?

All of Armstrong's inventions were involved in controversies. Lee de Forest got legal credit for regeneration (and others might have, with better counsel -- notably Robert Goddard.[1]) John Bolitho had discovered much of the superregeneration principle before Armstrong, who prudently bought Bolitho's patent before negotiating with RCA. FM had been gathering dust on theoreticians' shelves for decades before Armstrong took it up but, as soon as he had made it worth fighting over, he was beset from all sides. So, if the superheterodyne was his most valuable invention -- and it is fundamental to essentially every radio and television made since 1930 -- it would be surprising if Armstrong had *not* had his priority disputed.

The dispute ended in defeat. In 1928, Armstrong lost his superheterodyne patent in an interference proceeding within the Patent Office, when most of its claims were transferred to a Lèvy patent owned by AT&T. Since AT&T was in the same patent pool as Westinghouse and RCA, this transfer had no effect on the industry and attracted little notice.[2] Lèvy did not publicly press his claims outside of France and, even there, Armstrong often was credited with the invention.

In view of this apparent misappropriation of credit, it is worthwhile to take a careful chronological look at the superheterodyne to see precisely how it was invented and how it was introduced into practice.

THE HETERODYNE

First came the heterodyne. The principle of "beats" or difference tones between simultaneous audio pitches was well known since antiquity, but Reginald Fessenden, in 1901, was the first to apply the principle to radio transmissions.[3] Originally both radio frequencies were to be transmitted, received with two antennas, and combined in a detector.

Later, a local oscillator was substituted for one of the transmitter-receiver combinations and the heterodyne as we know it was born. Fessenden, himself, coined the term from the Greek *heteros* (other) and *dynamis* (force). For years, Fessenden was the lone proponent of continuous waves and possessed the only such transmitter -- the radio-frequency alternator later perfected by E.F.W. Alexanderson, of General Electric.

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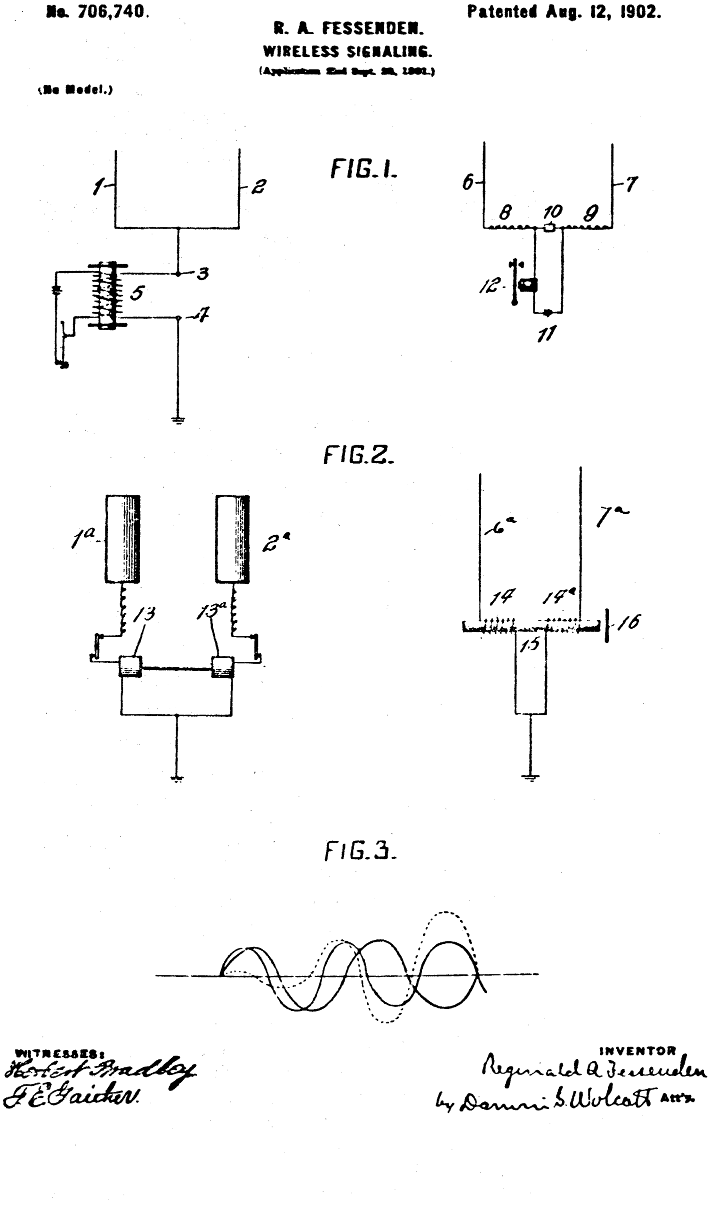
[1] A. E. Anderson, "Robert H. Goddard: Original Inventor-Patentee of the High Frequency Vacuum Tube Oscillator," (unpublished manuscript, 1981)

[2] It would not have affected most of the industry anyway, as RCA did not license other manufacturers under its superheterodyne patents until 1930. But it surely would have changed RCA's fortunes, if RCA and AT&T had not reached an amicable settlement of their broadcasting dispute, and if AT&T had therefore gone into the radio business, selling superheterodynes to the public.

Archer, *Big Business and Radio* (New York: The American Historical Co., 1939).

[3] U.S. Patent 706,740 filed Sept. 28, 1901, issued Aug. 12, 1902.

Cyril Elwell followed with his development of the arc generator, the basis of the Federal Telegraph Company. For its detector, Federal interrupted the incoming signal at a radio-frequency rate with a rotating commutator. The heterodyne worked better but had to await the development of suitable low-power local RF sources: small alternators, arc generators, or vacuum tube oscillators.



No. 706,740.

Patented Aug. 12, 1902.

R. A. FESSENDEN.
WIRELESS SIGNALING.
(Application filed Sept. [illegible])

(No Model.)

Heterodyne detection provided an apparent amplification of the received signal, an important effect since, at first, no other method of radio-frequency amplification was known (the Audion was used only as a detector for several years after its 1906 invention, not as an audio- or radio-frequency amplifier.)

From 1912 to 1915, radio engineers Hogan, Cohen, Latour and Liebowitz attempted theoretical explanations of heterodyne amplification, variously obtaining results of 1.27, 2, or 4 times the ratio of local-oscillator strength to received-signal strength. Not only did the numbers differ, but there also was disagreement on whether it was true amplification or a result of increased detector efficiency. The discussion in the *I.R.E. Proceedings* became more and more heated as the mathematical expressions lengthened. So Armstrong, ever distrustful of mathematics, set out to discover the truth for himself.

With a permanent teaching position at Columbia University as Michael Pupin's assistant, Armstrong had full use of a well-equipped engineering laboratory. He presented his experimental findings to the Institute of Radio Engineers in October 1916,[4] more or less corroborating Liebowitz' mathematics. Heterodyne amplifications of 100 or more were measurable which, in turn, could be increased fifty times in a regenerative-circuit connection. But most importantly, by the time Armstrong had finished his work, he was intimately familiar with the practical handling of heterodyne circuitry.

THE WAR

When the United States entered World War I, Armstrong joined the Signal Corps and was posted to France. The Division of Research and Inspection had just been created to evaluate existing apparatus and to propose changes, and to inspect equipment manufactured in Europe for the American Expeditionary Forces. Captain Armstrong was placed in charge of the Radio Group of the Research Section.

On his way to France, stranded for three days when fog closed the Channel, Armstrong had taken the opportunity to visit London. Stopping at the Marconi Company offices, he met Captain H.J. Round, for the war's duration in charge of a chain of wireless direction-finding stations for the Admiralty. Here, Armstrong came close to some of the war's best-kept secrets. For, using information supplied by these listening stations, the Admiralty could not only keep continuous track of many German ships and submarines but, also, had broken the German ciphers and could read nearly all the messages.[5]

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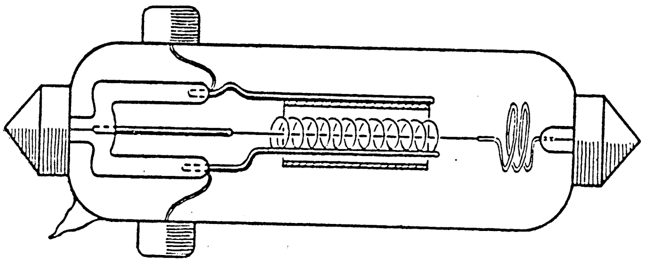
[4] Edwin H. Armstrong, "A Study of Heterodyne Amplification By the Electron Relay," *Proc. I.R.E.* 5 (April 1917), pp.145-168.

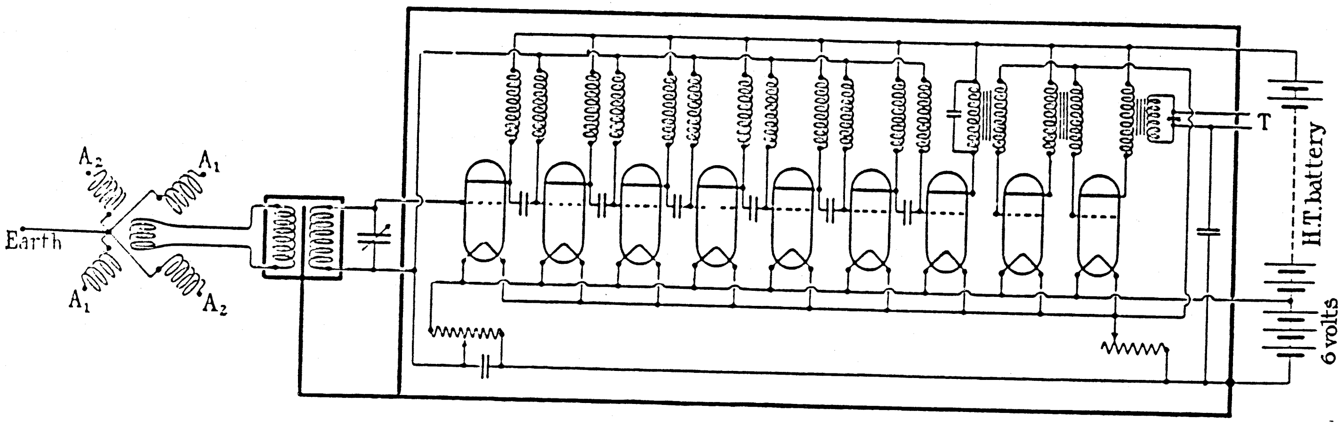
What most interested Armstrong, however, was Round's short-wave equipment. The Germans used low-powered "buzzer" sets for shipboard intercommunication while at anchor in their home ports, confident that they could not be heard more than a few miles on their 200-meter (1.5 MHz) wavelength. Round's multistage amplifiers, however, could pick them up and fix their positions. A small change in position could mean that a ship had moved downriver getting ready to put to sea (the largest naval battle of the war, the Battle of Jutland, was brought about because of a 1-1/2 degree change in bearing of the German flagship.) With advance warning of German sorties, the British could not only ready their defenses but, ideally, hoped to bring the German fleet to action against their own superior forces.

Round had been able to make such short-wave amplifiers operate by designing his own vacuum tube (the V24) with very low interelectrode capacitance. One of his standard amplifiers used eleven V24's in cascade for a total gain of 2,000 and, where more amplification was needed, two amplifiers could be connected in tandem. Some direction-finding stations ran as many as 130 tubes and used prodigious numbers of spares, not to mention battery power but, to the Admiralty, the results were well worth the expense.[6]



H.J. Round's V24 Valve, 1916

Such quantities of V24 tubes would never be available to the army in France and no American tube was remotely suitable for this RF amplifier service, but Armstrong sent the information back to the Signal Corps laboratories for future development. For the moment, the AEF settled on the latest French design by Marius Latour: a four-tube, six-stage model L-3. Armstrong's problem was immediate -- the German army was rumored to be using very short waves for front-line communication, waves too short to be picked up on the French receivers.



Round's Direction-finding Amplifier. Coils A1 and A2 were connected to large stationary single-turn loop antennas, 90 degrees apart.

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[5] Sir Arthur Hezlet, *Electronics and Sea Power* (New York: Stein and Day, 1975), pp.83-155.

[6] H.J. Round, "Direction and Position Finding," *Journal I.E.E.* 58 (March 1920), pp.224-257.

Since one regenerative detector tube would have performed nearly as well as Round's multistage creations, one may wonder why this was not done. After all, American hams had been operating on short waves for years (although truthfully, very few were anywhere near the legal boundary of 200 meters.) Paul Godley's "Paragon" receiver (grid and plate circuits tuned with self-resonant variometers for regeneration) was well known.

H.J. Round gave two explanations in 1920: the multistage amplifiers were less microphonic than a single tube, and an oscillating detector directly coupled to an antenna could have wiped out other direction-finding stations trying to pinpoint the same signal[7].

One more bit of knowledge is needed to set the stage for Armstrong's discovery: the heterodyne was not considered suitable for spark reception. Spark signals were somewhat like present-day AM in that they were modulated at an audio rate and occupied a large bandwidth. Tuning a heterodyne detector to a spark signal's center frequency was out of the question. Neither the signal nor the local heterodyne oscillator had anything like the necessary stability and, in addition, there was no obvious way to tell when zero-beat was achieved. A mis-tuned heterodyned spark signal had a raspy, hissing sound, much more difficult to read than an audio tone, and not easily distinguished from interfering signals or atmospherics.

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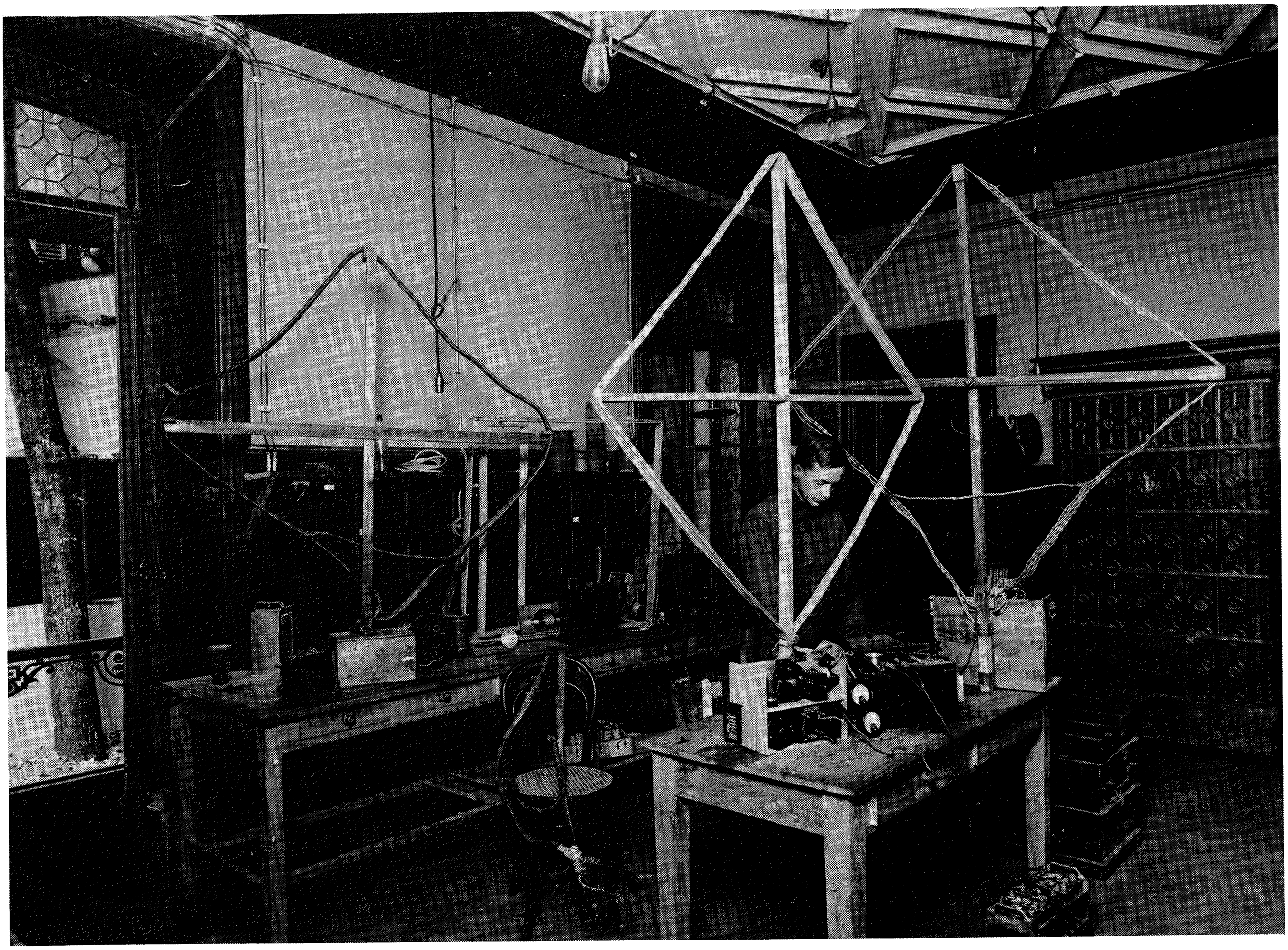
[7] H. J. Round, "Direction and Position Finding," *Journal I.E.E.. 58 (March 1920), p. 240.*



Armstrong's Paris Laboratory (U.S. Army Signal Corps photo)

THE INVENTION

As Armstrong later explained it, his conception of the superheterodyne was the result of three chance occurrences. First, he knew all about heterodyne circuitry. Second, his London meeting with H.J. Round had set him thinking about reception of weak high- frequency signals. As he related in 1943:

> "The third link came months later as I happened to be watching a night bombing raid and wondered at the ineffectiveness of the anti-aircraft fire. I might say that night bombing was not very dangerous in those days either for the man on the ground or the man in the airplane. Thinking of some way of improving the methods of locating the positions of the airplanes, I conceived the idea that perhaps the very short waves sent out from them by the motor ignition system might be used.
>
> "The unique nature of the problem, involving the amplification of waves shorter than any ever even contemplated and quite insoluble by any conventional means of reception, demanded a radical solution. All three links of the chain suddenly joined up and the superheterodyne method of amplification was practically forced into existence. Not one link in the chain could have been dispensed with. This, I think, is the only completely synthetic invention I have ever made." [8]

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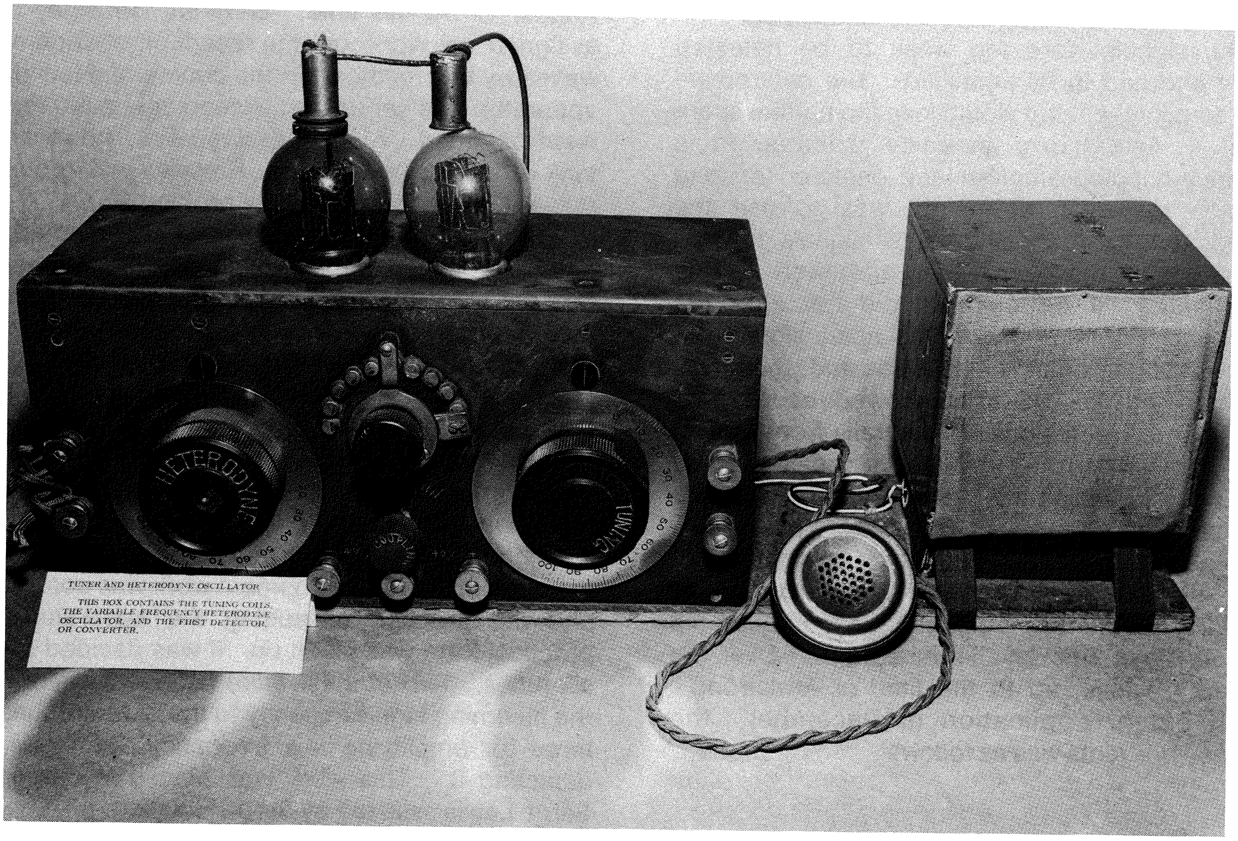
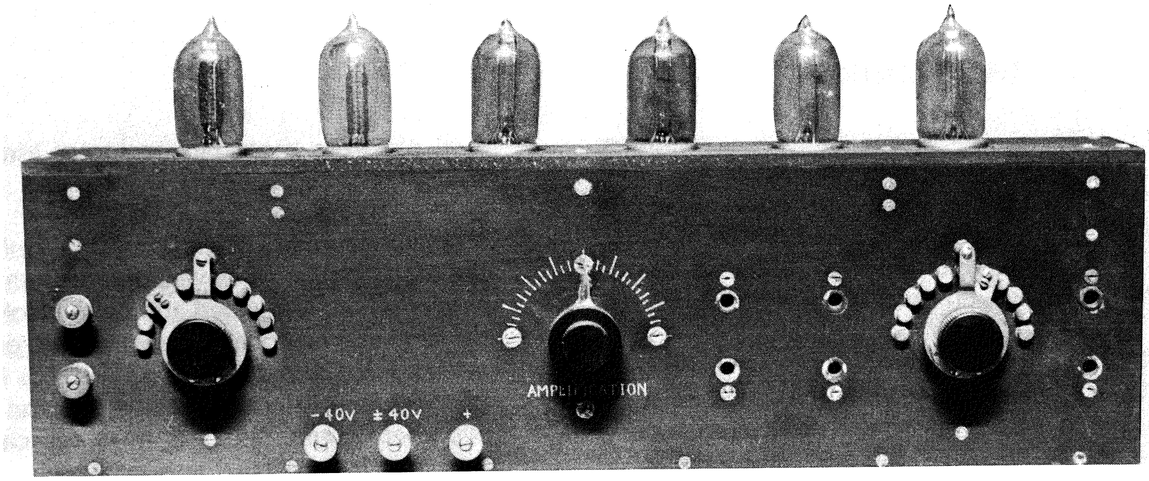
[8] Armstrong, "Vagaries and Elusiveness of Invention," *Electrical Engineering* 62 (April 1943), p.150.


HETERODYNE
COUPLING
TUNING
TUNER AND HETERODYNE OSCILLATOR
THIS BOX CONTAINS THE TUNING COILS, THE VARIABLE FREQUENCY HETERODYNE OSCILLATOR, AND THE FIRST DETECTOR OR CONVERTER.

One half of Armstrong's first Superheterodyne Model, as it was displayed at the Army Communication Museum at Ft. Monmouth, New Jersey in 1980. The right-hand box, the headphone, and the VT2 tubes with the caps resting on them, are all incorrect, but the set has been displayed this way since at least 1954. This model, with its four-tube amplifier box, is shown in its original condition in *Radio News*, Feb. 1920 reference 15.

(U.S. Army photo, courtesy of H.L. Chadbourne)



Armstrong's Second Model, now in the Smithsonian. (Photo by Donald Paterson, *Radio Age*)

This happened in Paris in March 1918 as he was walking back to his apartment after watching the air raid. Years later, he swore he could find in the dark the particular street where the thought had come to him, if set down in the city blindfolded.

The signals were too weak to be detected directly and had to be amplified. The heterodyne would amplify them but would lose the natural spark tones. Armstrong already possessed a resistance-coupled amplifier and detector for long waves. His flash of insight was to use the heterodyne to bring the short-wave signals down to the range of his long-wave amplifier. This heterodyning, it turned out, did not alter the modulation content of the original spark signals but preserved all the original sidebands and, therefore, the characteristic tone that allowed each spark transmitter to be distinguished aurally from others. The final detection now could be done by rectification in the normal manner[9] because there was a large amplified signal available.

That was the invention, but a great deal of experimentation was needed to prove its workability. Armstrong proposed the method to his superior, Major Buckley, in June 1918. Over the next few months, up to the time of Armstrong's French patent application in December, the sequence of events was as follows:

"Preliminary experiments which showed the practicability of the method were made at this time but, on account of the large amount of more pressing work, they were discontinued until about August 1. At this time, Sergeant Pressley was assigned to work on the reception of undamped waves by this method. In the course of a few days, apparatus was set up and exceedingly good results were obtained. More pressing work, however, in tank radio, for which Sergt. Pressley was required, prevented continuation of the problem.

"The development of the method for receiving damped and modulated continuous waves was the next step. On account of the fact that no men capable of handling the work were available, this development was turned over to Sergt. MacDonald who was regularly stationed at Orly Field but who volunteered to work on the problem in his own time. The lack of help greatly delayed the development. Toward the middle of August, Sergt. Lewis was available and was also assigned on the development. About the middle of September, the experimental and development work was completed and the problem of putting the apparatus into practical form was taken up. It was decided to use six tubes. Two of these were used in transforming the incoming high frequency to the lower frequency, three for amplifying this frequency, and one for detecting it. This work was placed in charge of Sergt. Lewis assisted by Sergt. Houck.

"On account of many unforeseen difficulties and the great amount of work required to complete the detail design of the various parts, the first model was not turned out until about the 1st of November. In preliminary tests, the model gave several thousand times the amplification of the L-3, and the advantage could be increased by the addition of a two-stage audible-frequency amplifier. Tests were completed, and it was ready for trial at the front at the time of the signing of the Armistice."[10]

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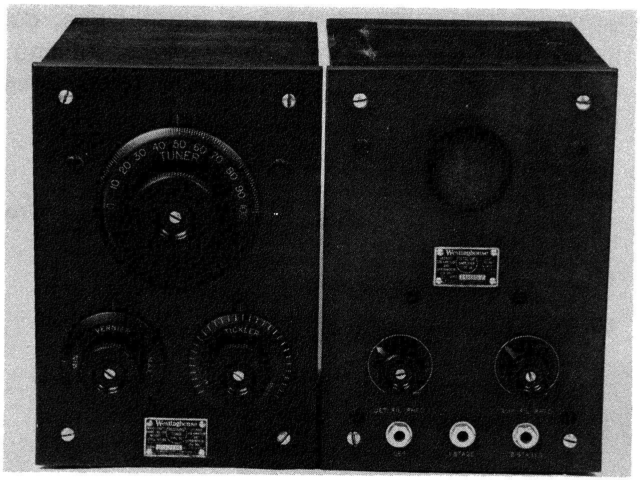
[9] Normally a grid-leak detector would have been used, which amplified as well as detected, but Armstrong had used crystal rectifiers in his heterodyne researches. Any device, worked over a nonlinear portion of its characteristic, would partially rectify an applied signal, and serve as a detector.

PUBLICITY

Armstrong returned to the United States in time to present a paper to the Institute of Radio Engineers on December 3, 1919, outlining his new system. He concluded the talk:

> "The new practice of this method involves the use of many known inventions but, in connection with the production of a superaudible frequency by heterodyning, I wish to make due acknowledgment to the work of Meissner, Round, and Lèvy, which is now of record. The application of the principle of reception of short waves is, I believe, new and it is for this reason that this paper is presented."[11]



Westinghouse Model RA Tuner and DA Three-tube Detector-Amplifier, designed in 1920 and sold in large numbers for several years.

During all of 1920, Armstrong was preoccupied with his regeneration patent and, particularly, his legal problems with Lee de Forest. Having little income to pay his mounting bills, he needed an ally. He is said to have approached the large independent radio manufacturer Amrad, backed by J.P. Morgan, Jr., with an offer of a half interest in his regeneration patent for $ 500.[12]

But then his attorneys hit upon the idea of licensing all the makers of regenerative ham receivers and, by September, had signed up 18 of them, assessing a royalty of 5% of sales price. At that time, the Amateur market was negligibly small and some licensees were no more than high-school boys working in their attics. The fact that they might grow up to become such firms as Crosley and Zenith was unforeseen.

Armstrong found his ally in Westinghouse. Having become involved in radio during the war and wishing to set up a world-wide communication business like the British-controlled American Marconi Company, Westinghouse invested heavily in Fessenden's old company and its valuable patents, only to be checkmated by its rival, General Electric. GE, with the Navy's blessing, had formed RCA from the American Marconi Company. RCA, in June 1920, concluded cross-licensing agreements with GE and AT&T and signed exclusive traffic agreements with nearly every important country in the world before Westinghouse could blink its eyes.

Westinghouse executives, however, were not myopic. Frozen out of the commercial field, they began radio broadcasting to create a market for their manufactured radio sets, and moved quickly to strengthen their bargaining position with RCA and its allies by purchasing Armstrong's regeneration and superheterodyne patents in October 1920.[13] It is tempting to assume that Westinghouse appreciated the advanced technical features of the superheterodyne and was therefore willing to spend so much money on the patent, but it is more likely that regeneration was the real prize, and that Armstrong insisted on a package deal.

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[10] *Report of the Chief Signal Officer, 1919* (Washington, Government Printing Office, 1919. Reprint by Arno Press, New York, 1974), pp.288-289.

[11] Armstrong, "A New System of Short Wave Amplification," *Proc. I.R.E.* 9 (Feb. 1921), pp. 3-27. *QST* 3 (Feb. 1920), pp.5-9, 15.

This paper uses the term "superaudible heterodyne," from which "superheterodyne" is derived. The British tended to use "supersonic." Incidentally, the first use of the word "superheterodyne" that I have seen, is in *QST* for March 1921 (p.41) but evidently from the context it was in common use by then.

[12] Amrad's boy-wonder president H.J. Power declined Armstrong's offer. Douglas, *Radio Manufacturers of the 1920s*, Vol.I (Vestal, NY: Vestal Press, 1988), p39.

[13] Option purchased on October 5, exercised November 4, 1920 for $335,000 plus $200,000 if Armstrong should win his interference with de Forest over the regeneration patent. The purchase included 4 issued patents and 16 applications by Armstrong, Pupin, or the two jointly.

The company's broadcast radio models, already designed and in production, could not be marketed without either a patent license or ownership. Westinghouse made no use of the superheterodyne patent and, for a time, neither did anyone else.

In the February 1920 issue of *Wireless Age* (affiliated with American Marconi/RCA and generally considered authoritative), Paul Godley described Armstrong's system in some detail.[14] Godley had been with American Marconi during the war as its receiver expert. He was a partner in the Adams-Morgan Company, the country's foremost maker of ham receivers, and had been the first to make Armstrong's regenerative circuit work on short (200 meter) waves. Simultaneously, the February and March issues of *Radio News* (published by Hugo Gernsback and aimed more at young hams and tinkerers) carried lengthy articles by Harry Houck who had been Armstrong's assistant in France.[15]

But other than establishing Armstrong as the originator of yet another advance in radio technology, these published articles seemed to have little effect. In those days when the average amateur counted himself lucky to afford even one vacuum tube, the idea (and expense) of running six or eight of them must have seemed quite far-fetched.

On October 29, 1920, the Wireless Society of London discussed the superheterodyne. *Wireless World* in London published a report on November 13,[16] and finally in February 1921 the I.R.E. published Armstrong's 1919 paper.[11] Still no hint that the circuit had any practical civilian uses.

The 1921 A.R.R.L. transatlantic tests woke people up. The idea that a bunch of rowdy kids with limited equipment, wavelengths, and power could accomplish what the commercial interests supposedly could not -- "get across" -- gave these amateurs swelled heads for decades afterward.[17] (Actually, much experimentation with short waves had already been done and Marconi, himself, probably knew as much about them as the hams did.)

QST magazine was filled with the exploits of Paul Godley who had been sent to Scotland especially for the tests, and who had used.....a superheterodyne ![18] *Wireless World* for February 4, 1922 likewise ran a long story on the equipment and the results.[19] Superheterodynes began to acquire some mystique. However, they were still very expensive. Vacuum tubes, for instance, cost $5.00 to $7.50, and with tube filaments drawing 1 ampere each, upkeep of batteries alone would break most piggybanks.

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[14] *Wireless Age* 7 (Feb. 1920) pp. 11-14.

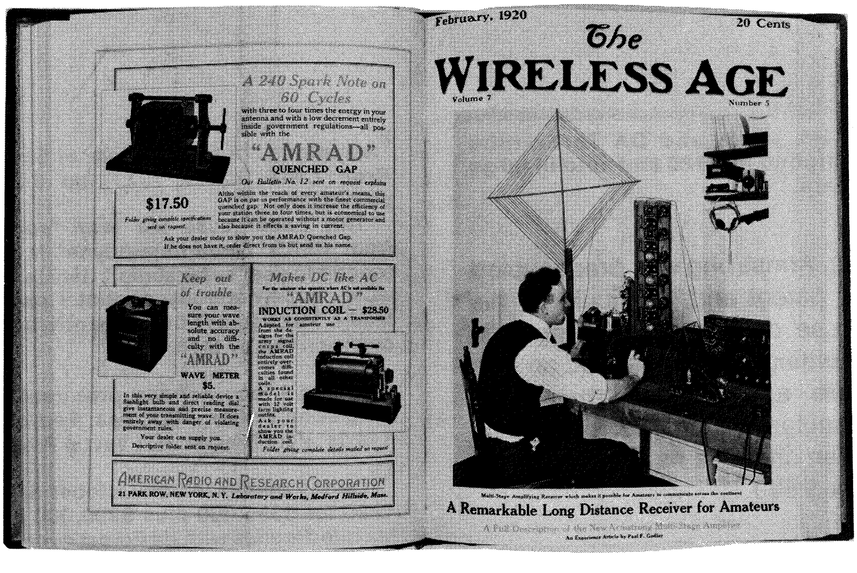
[15] *Radio News* 1 (Feb. 1920) pp.403-405,439; (March 1920) pp. 469-471, 508-510.

[16] *Wireless World* 8 (Nov. 13, 1920) pp. 581-583.

[17] DeSoto, *Two Hundred Meters and Down* .(West Hartford, CT: The American Radio Relay League, 1936).

[18] *QST* 5 (Feb. 1922) pp.7-40.

[19] *Wireless World* 9 (Feb.4, 1922) pp.689-694



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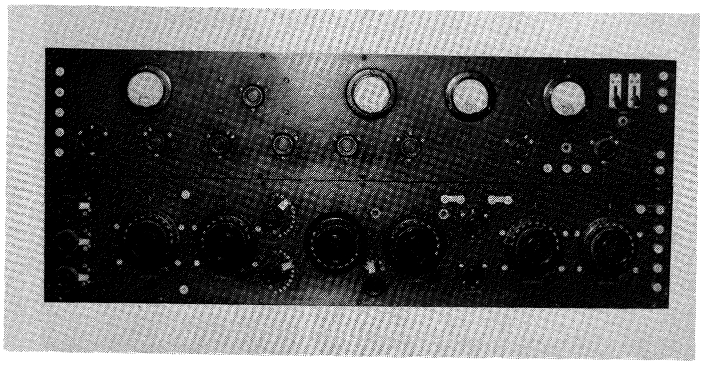
February, 1920 20 Cents

The WIRELESS AGE

Volume 7 Number 5

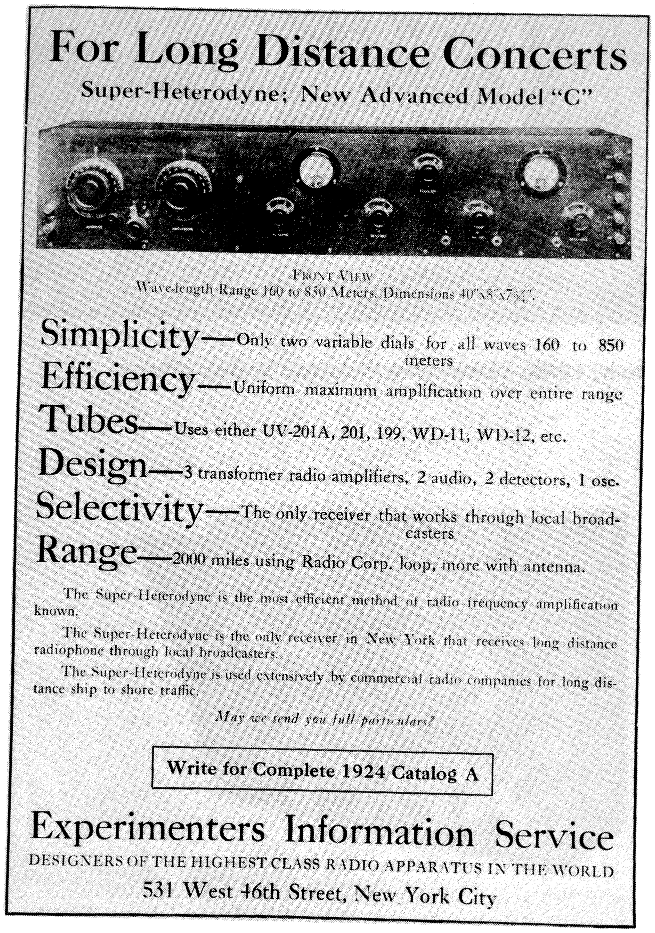
A Remarkable Long Distance Receiver for Amateurs

Paul Godley with an experimental superheterodyne. This volume of *Wireless Age* (one of a complete set) was discarded by the Columbia University Library and might very well have been used by Armstrong.



Leutz model L, 1922 (Howard Hein collection, photo by H. L. Chadbourne)

Below, **Leutz model C,** *Radio News*, July 1923



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POPULARITY

In early 1922, the radio boom hit America. Radio broadcasting, which earlier had interested mainly kids, now began to appeal to a far wider and more affluent audience. Armstrong, himself, termed his new circuit "the Rolls Royce method of reception" and, like the automobile, the superheterodyne attracted many patrons precisely because of its expense and complexity.

RCA, which could have sold superheterodynes, refused because Elmer Bucher, its sales manager, insisted that his models must have no more than two tuning controls to be simple enough for the public to operate.[20] RCA did commission GE to build a commercial model designed by A. F. Van Dyck in 1921, and installed with appropriate fanfare on the passenger liners *Leviathan* and *America* in early 1922. But of course this was far from a domestic radio.

First to cater to the public taste in RCA's absence, was Charles Leutz, formerly Godley's assistant at American Marconi. Leutz introduced his model in September 1922, updating it every few months with the latest improvements. He dared not sell complete radios for fear of a patent-infringement suit, but he did a thriving business in blueprints, components and kits, publicizing his wares in full-page ads and in a popular series of books titled *Modern Radio Reception*.

Modern it may have been, but his first model was certainly not for novices; it had six tuning dials and seventeen other controls. Elmer Bucher singled it out as a prime example of what the public did *not* need. Leutz' 1923 model was vastly simpler, and more successful.[21]

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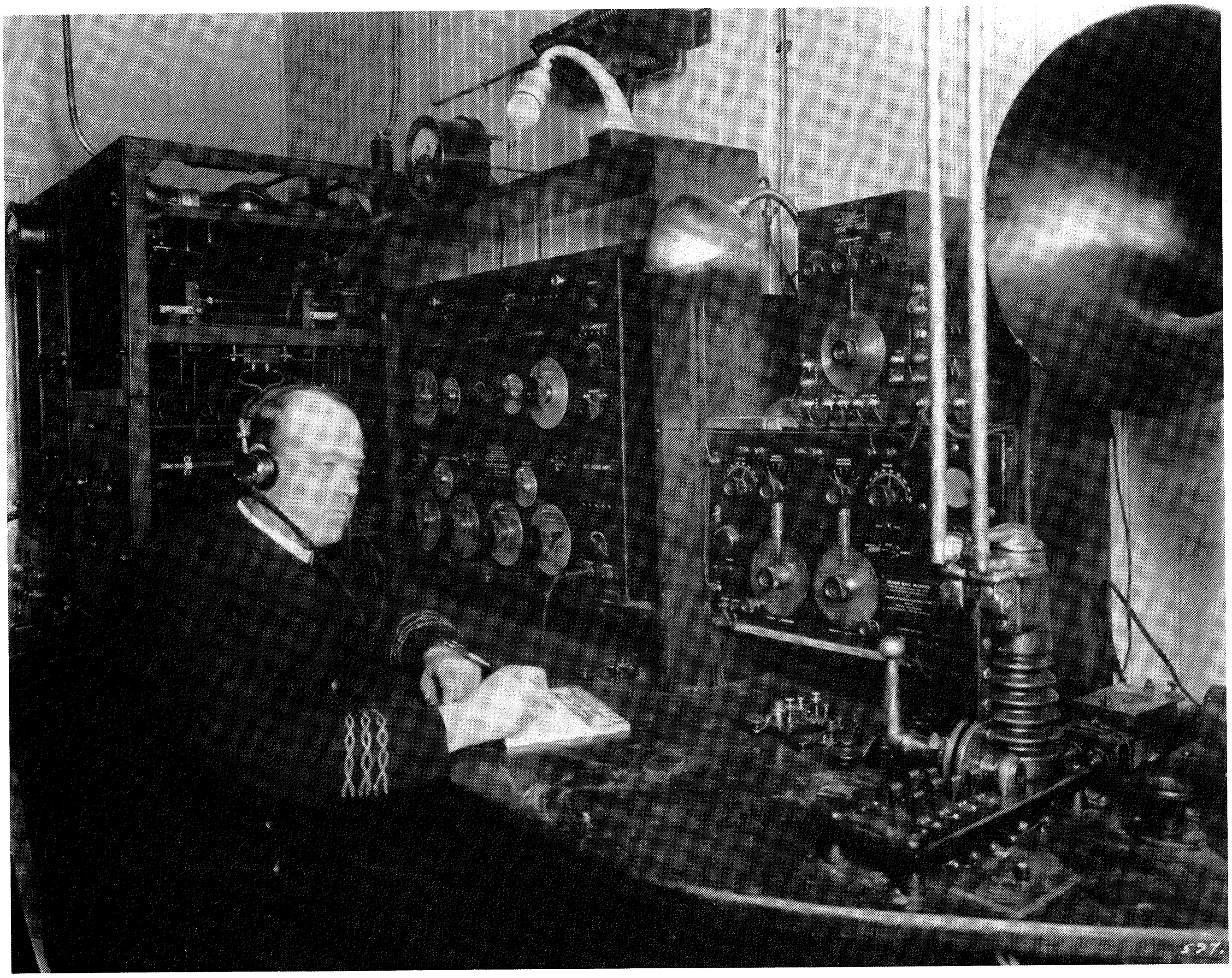
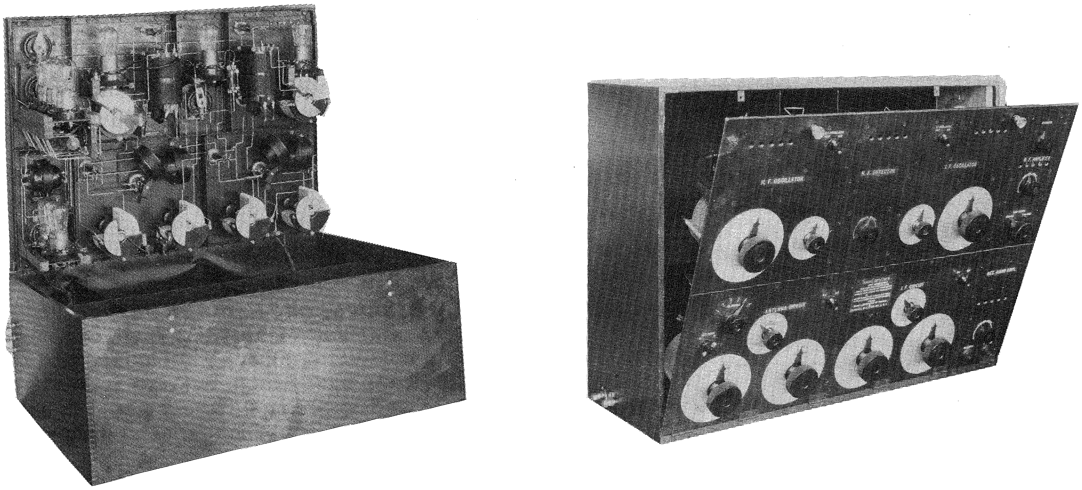
[20] *Big Business and Radio*, p.92.
RCA nonetheless marketed its share of complex apparatus. The Radiola VI from this period indeed had only one tuning dial and one bandswitch, but also sported an amplification control and six filament rheostats. It sold for $162.50 without antenna, tubes, batteries, or speaker.

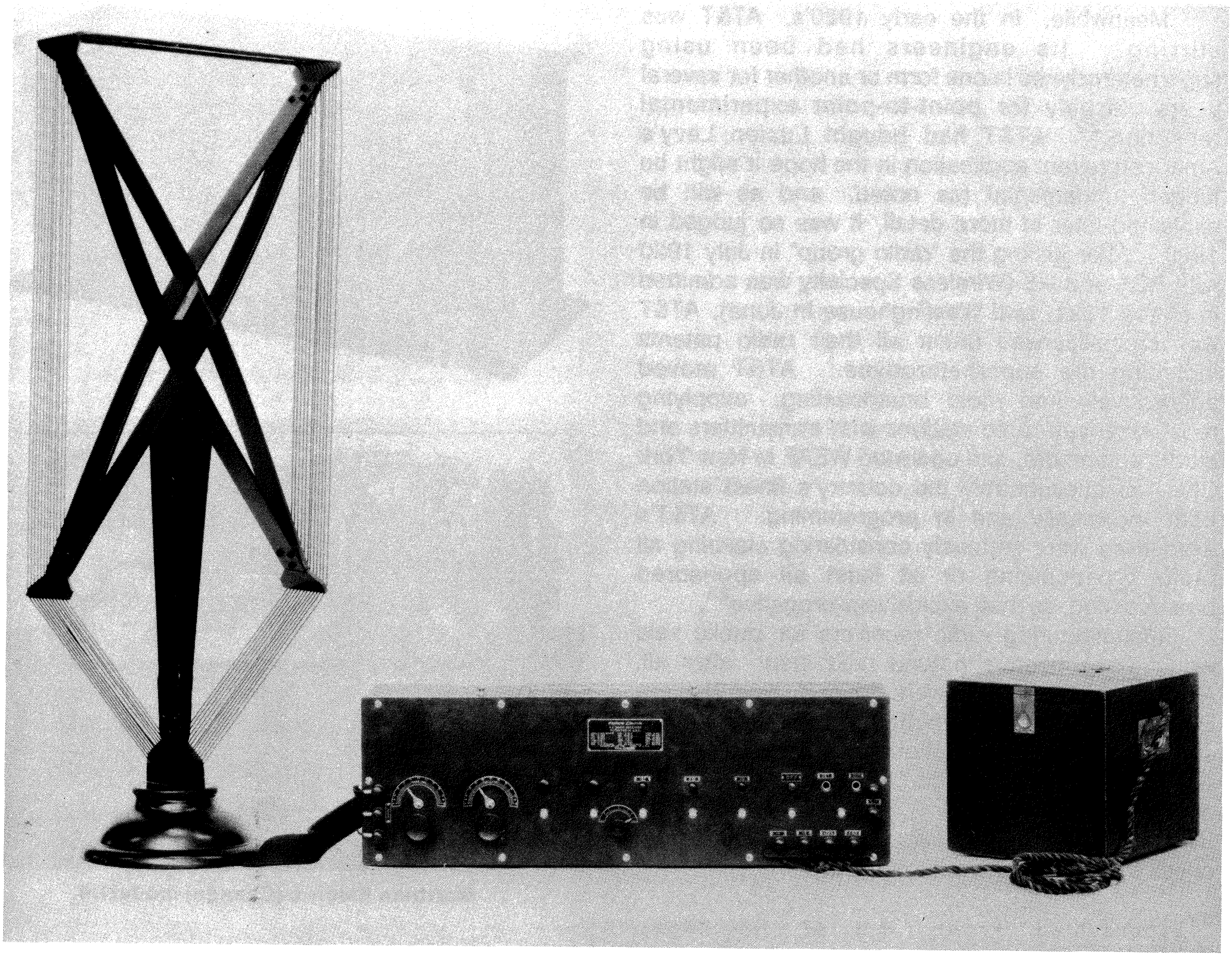
[21] For a detailed story of Leutz' career and radio models, see Douglas, *Radio Manufacturers of the 1920s*, Vol. 2 (Vestal, NY: Vestal Press, 1989), pp. 122-131.



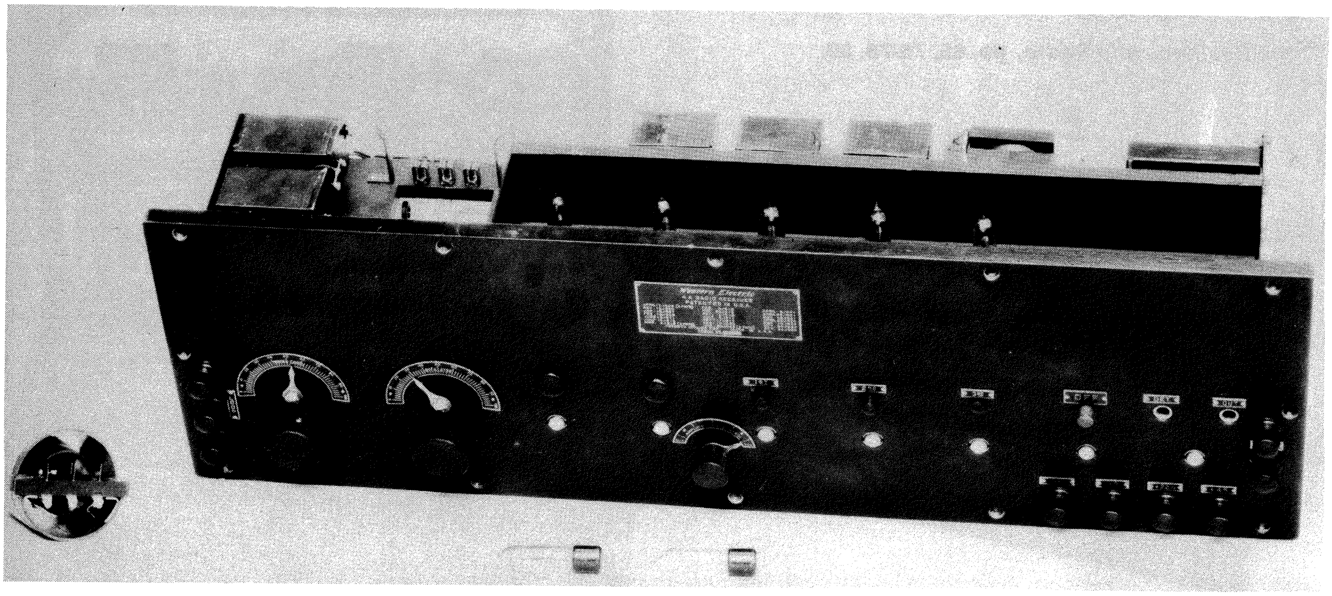
Elmo N. Pickerill in the radio room of the S.S. Leviathan, 1923. (Steamship Historical Society photo).



Model of Radio Receiver for Duplex Operation Model No. 2RF/D/21F/3-8/3RDA/A



Super Heterodyne Receiver Manufactured by Western Electric Company, showing complete equipment.



Western Electric model 4A (photos courtest Hall of History, Schenectady, NY)

Meanwhile, in the early 1920's, AT&T was stirring. Its engineers had been using superheterodynes in one form or another for several years, largely for point-to-point experimental reception.[22] AT&T had bought Lucien Lèvy's American patent application in the hope it might be judged fundamental (as noted, and as will be explained later in more detail, it was so judged in 1928.) After joining the "radio group" in July 1920 with RCA and GE (Wireless Specialty was admitted in March 1921, and Westinghouse in June), AT&T was cross-licensed under all their radio patents including the superheterodyne. AT&T moved aggressively into radio broadcasting, supplying most American radio stations with transmitters and studio equipment, and operated WEAF in New York City -- unquestionably the country's finest station both technically and in programming. AT&T's executives were seriously considering claiming all radio broadcasting or at least all sponsored broadcasting, as their exclusive prerogative[23].

Manufacturing radio receivers for public sale would have been a natural next step; after all, AT&T's foreign affiliates were doing it. And Western Electric was already building receivers to be supplied to broadcast stations as part of their studio equipment. All stations had to monitor the 500 kHz marine distress frequency, and shut down in the event of an SOS; they also used the receivers to check their own transmission quality.

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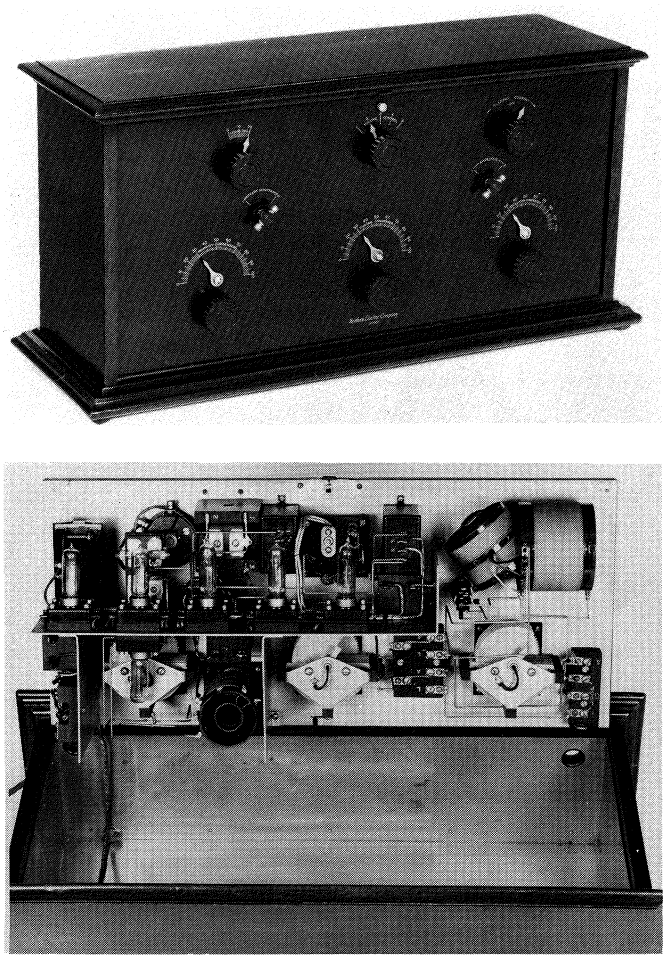
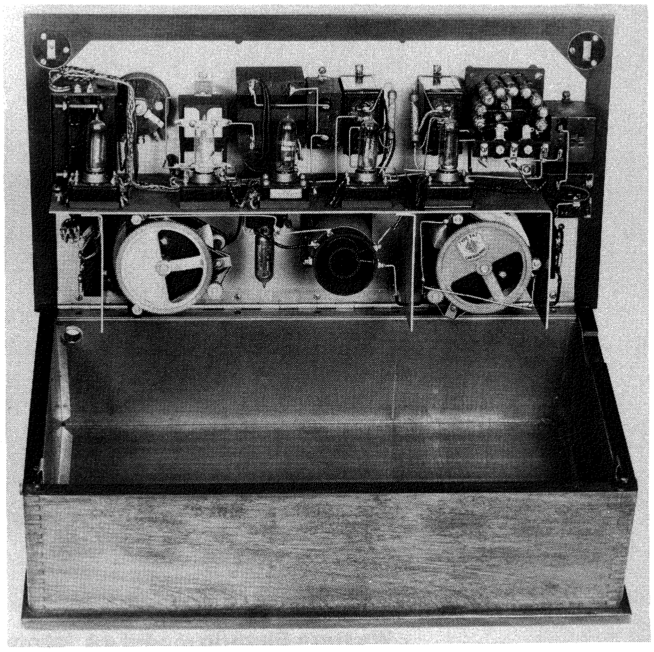
[22] Espenschied, *Proc. I.R.E.* 47 (July 1959), pp.1257-1258.
A History of Engineering & Science in the Bell System. The Early Years (1875-1925) (Bell Telephone Laboratories, 1975), pp. 349-465.

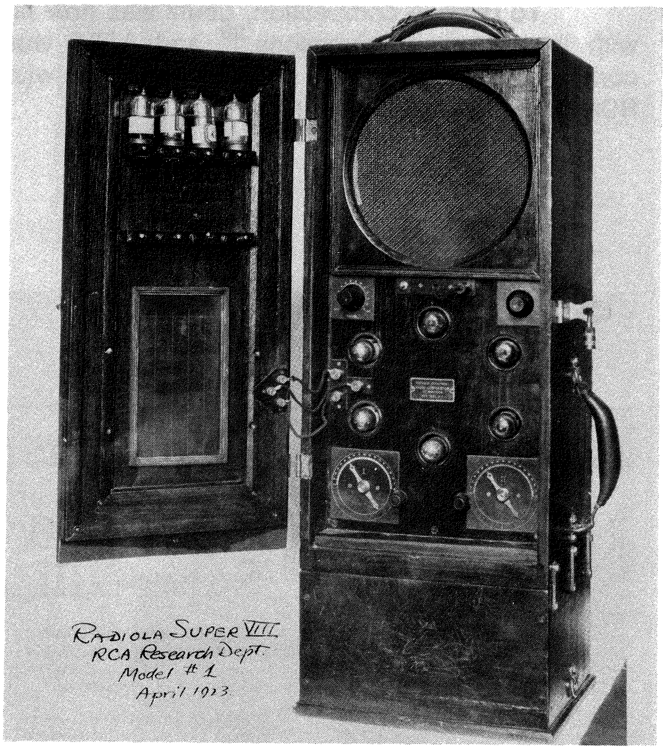
[23] *Big Business and Radio*, pp. 55, 75-78, 89.



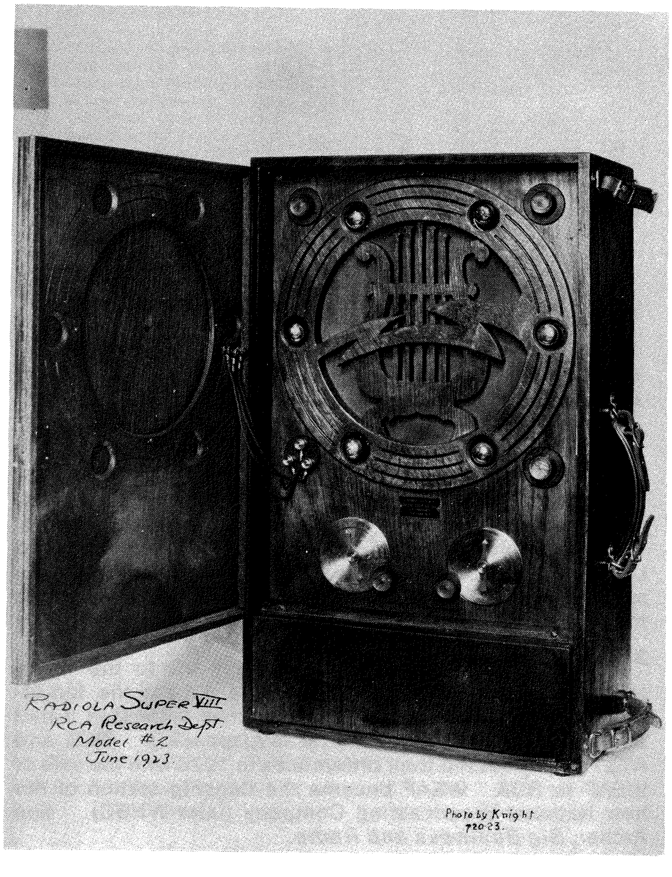
Northern Electric (Canada) model R4.

Below, **Western Electric 4D**





A.F. Van Dyck moved from GE to RCA in 1922. One of his pet projects was a portable superheterodyne; the two models shown were evolved by 1925 into the Radiola 26.



Basing their design on a portable field-strength-measuring receiver, Western Electric's engineers created a seven-tube superheterodyne Model 4A by October 1922. One was sent in January 1923 to Dr. Alfred Goldsmith, RCA's Director of Research, and rumors circulated that another was about to be installed in the White House.

The cross-licensing agreements among the "radio group" members had been drawn up before radio broadcasting was thought important and, while some categories such as radio transmitters were carefully defined, the companies' respective rights to build and sell radio receivers to the public were not so clear.

AT&T wanted to get its nose into the tent. Its superheterodyne was said to have given RCA's sales manager Elmer Bucher "the jitters" which, considering RCA's archaic model lineup at the time, was probably true. RCA's affiliates GE and Westinghouse, which did all the actual design and manufacturing, had planned more of the same for next year's model line.

RCA's GAMBLE

But, in February 1923, just a month after Goldsmith had seen Western Electric's 4A, Howard Armstrong walked into David Sarnoff's office at RCA with his own simplified model. By using WD11 tubes and combining functions, he had whittled his model down to a (just barely) portable.[24] It would need further work to adapt it for commercial production -- much more, in fact, than anyone thought -- but it looked feasible and Sarnoff convinced his associates to take the gamble. He canceled millions of dollars' worth of just-placed orders with GE and Westinghouse, hoping to scoop the industry with a model that no one else could match.[25]

Time was very short to be designing an entirely new radio model for the 1923 - 1924 season. Most manufacturers tried to have their engineering done by June, to take orders during the summer, and to run their factories from September through December. Neither GE nor Westinghouse was especially fast on its feet, yet RCA expected them to scrap their existing designs and put an untried circuit into commercial form in three or four months !

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[24] Figs. 9 and 10 in Armstrong's 1924 I.R.E. paper (reference 32). The Westinghouse WDII was electrically equivalent to Western Electric's 215-A "peanut" tube, drawing .25 ampere at 1.1 volts from dry cells. GE's belated answer, used in all its portable sets including the superheterodynes, was the UV199 which consumed .06 ampere at 3.3 volts. The standard radio tube of the day, the UV201A, drew .25 ampere at 5 volts from a storage battery.

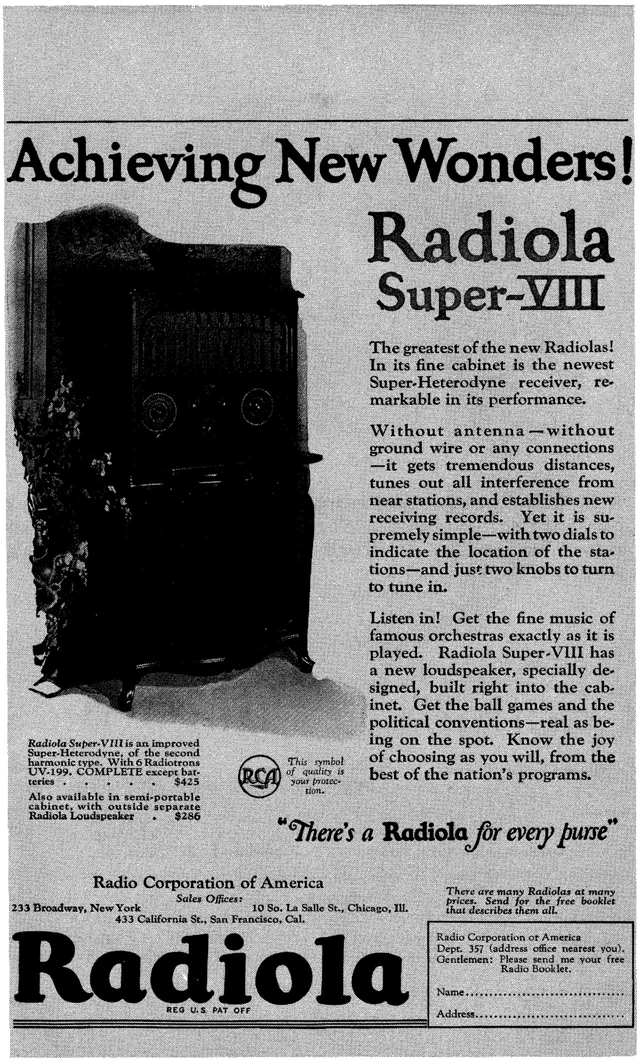
[25] Archer, *History of Radio to 1926* (New York: The American Historical Society, 1938), p.297.

Westinghouse declined[26] and, for a time, GE wished it had done the same. At one point during the development, the GE engineers were ready to give up, a sentiment echoed to Sarnoff by the usually-optimistic Goldsmith. A blank look and the question "What'll I do now?" by Sarnoff to his secretary Marion MacInnis brought the response, "Why not call Armstrong ?"[27]

He did and, along with Hull and Langmuir of the GE Research Laboratory, Armstrong helped solve the problem of hiss in the mixer tube[28] while his associate Harry Houck solved the oscillator-pulling with his "second harmonic" invention.[29] For this bail-out work, the two received an additional 18,900 RCA shares, making Armstrong the company's largest stockholder. And Howard did even better: he married Marion MacInnis.

As the 1923 Christmas selling season came and went with nothing available but last year's leftover turkeys, Sarnoff must have been besieged by RCA's panic-stricken dealers. But in February 1924 the new lineup finally appeared. It was a tremendous success with the eventual production of 148,300 superheterodynes, and made more money for RCA than anything up to the AC-powered sets of 1927 - 1928.

To remove competition, Leutz was now hit with lawsuits and injunctions,[30] and AT&T was convinced not to upset the ongoing arbitration with RCA by publicizing its new 4B model.[31]



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[26] Author's correspondence with W. L. Carlson, superheterodyne design engineer at GE, 1924-1930.

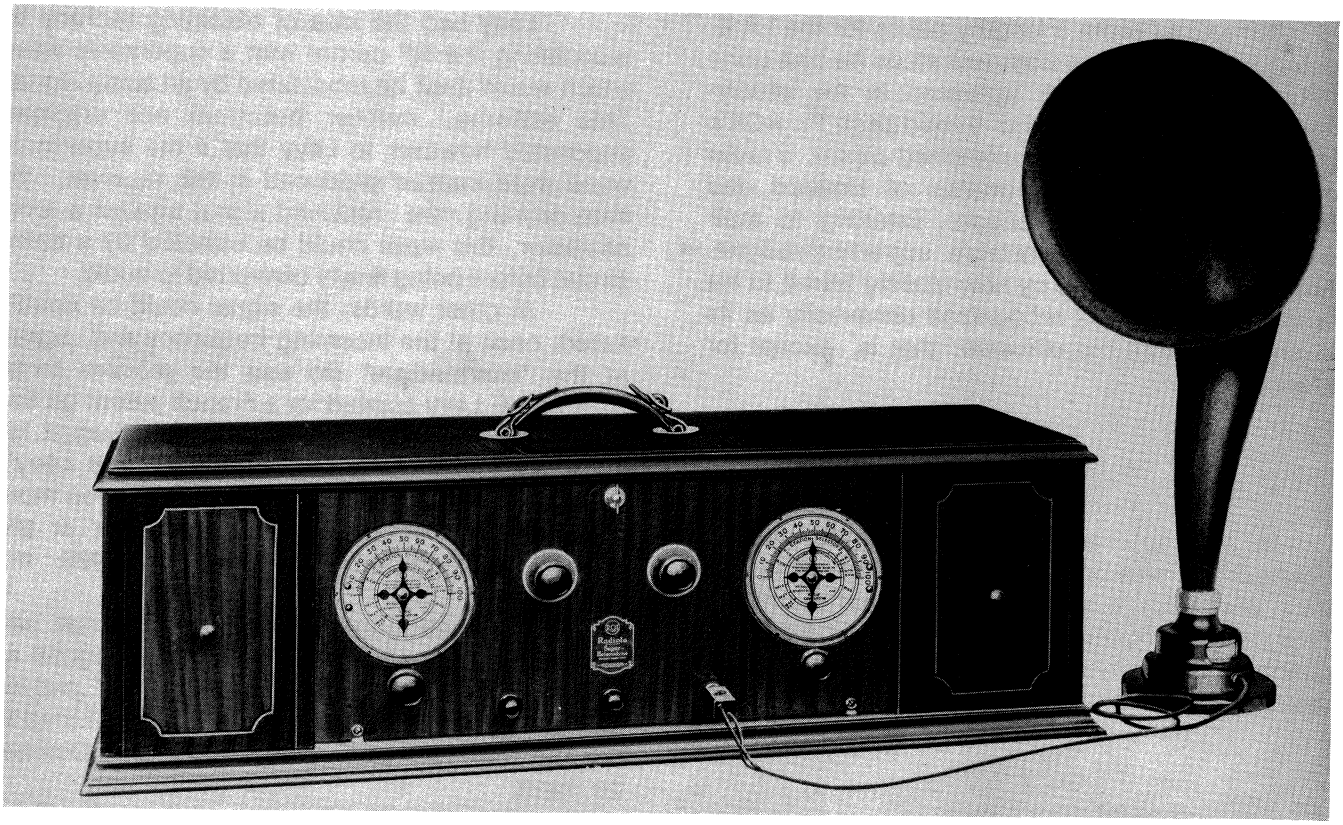
[27] Lessing, *Man of High Fidelity: Edwin Howard Armstrong* (Philadelphia: Lippincott, 1956. New York: Bantam Books, 1969), p.148/119.

[28] Hull's screen-grid tube grew out of this work. See *Physical Review* 27 (April 1926) pp.432-438, 439-454. Also *Proc. I.R.E.* 16 (April 1928) pp.424-446; 16 (June 1928), pp. 840-843.

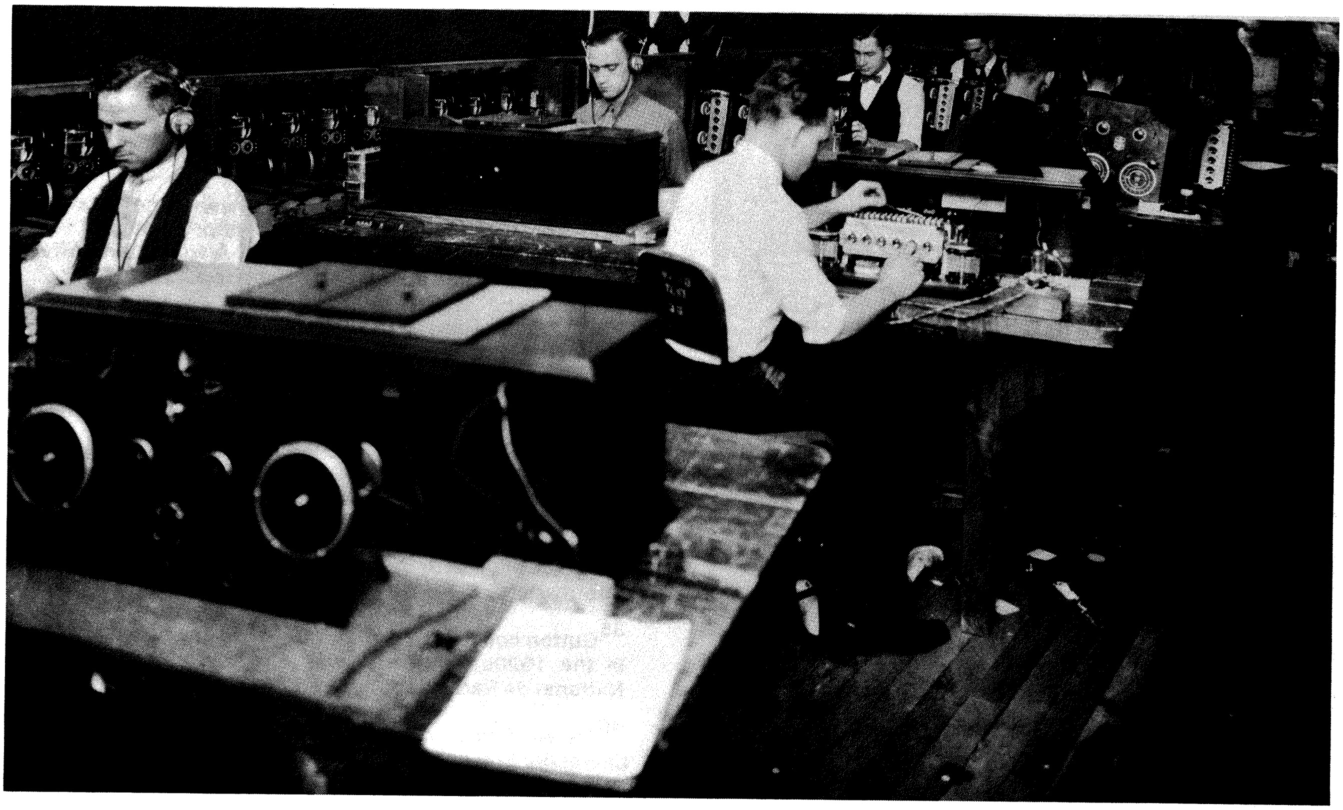
[29] To allow use of silicon-steel transformer cores, and to get the proper bandpass, the IF was set at 42 kHz. To economize on tubes and battery power, one triode served as oscillator and mixer, and the RF tube was also the first IF amplifier. But it proved impossible to avoid interaction between the RF and oscillator tuned circuits, only 42 kHz apart. Houck's solution was to run the oscillator at half the usual frequency, so that its second harmonic was 42 kHz from the RF signal. One disadvantage of this arrangement was that a station could be tuned in at several points on the dials, but at that time there were fewer stations on the air than now. These models in fact work quite well.

[30] RCA had already incurred Congressional wrath with its monopolistic practices, prompting a full-scale Federal Trade Commission investigation in 1923. If it had sued Leutz in 1923 before its own superheterodynes were on sale, RCA would surely have been denounced as a dog in the manger.

[31] This time AT&T actually delivered a 4B to the White House, to RCA's consternation since it beat the top-of-the-line Radiola Super-VIII in competitive tests (but it had three more tubes, and a better loudspeaker). RCA and AT&T finally settled their differences in 1926 with the sale of WEAF to RCA. WEAF became the flagship station of the new National Broadcasting Company (later WNBC). See Archer, *Big Business and Radio.*



RCA Model AR812, 1924 (RCA publicity photo)

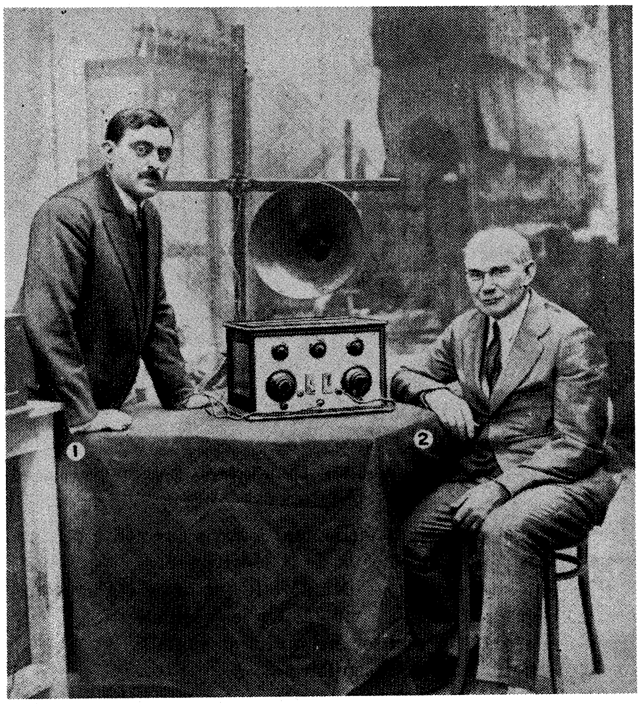


Assembling and Testing Radiola Superheterodynes at GE. (photos courtesy Hall of History, Schnectady, NY.)

Armstrong wrote a lengthy paper for the I.R.E. detailing the many development steps he had gone through and this paper appeared in the widely-circulated magazine *Radio Broadcast.*[32] RCA's considerable ballyhoo even reached Japan; a radio magazine there printed photos of Howard and Marion on the Florida beach, listening to their wedding present, a portable superheterodyne. Armstrong's name was by now closely linked to his creation and he was recognized universally as its inventor. In all the universe, that is, except for France.

FRANCE

In France, an entirely different line of development was going on, dating from 1916. In that year, Lucien Lèvy, an officer with the Telegraphie Militaire, was working on the 1-1/2 kW radiophone transmitter at the Eiffel Tower, under the direction of Col. Gustave Ferrie.[33]



Lucien Lèvy presenting Lee de Forest with one of his superheterodyne models (Hemardinquer, La Superhèterodyne et la Superreaction, 1926, p.166. Copy courtesy of the John Crerar Library, Chicago)

Lèvy had the idea of obtaining secrecy by modulating the RF carrier with a supersonic wave which would itself be modulated by an audio signal. This scheme, neither practical nor original, suggested however to Lèvy that if the supersonic wave were instead produced in the receiver, by heterodyning the received signal against a local oscillator, this wave could be selected by a tuned circuit before being finally converted to audio.

In other words, the signal could be doubly tuned: once at the incoming frequency and, again, at the "intermediate" (to use the modern term) frequency. Lèvy applied for a French patent on this arrangement on August 4, 1917 (issued August 19, 1919, no. 493,660).[34] On October 1, 1918, Lèvy's second French application disclosed an even more elaborate multistage amplifier and filter at the intermediate frequency (issued May 27, 1920, no. 506,297.)

Information on Lèvy's original circuit had been publicized among his military colleagues as one page of a report by C. Gutton[35] in 1917, and his final scheme in a hectographed paper distributed to the AEF Radio Research branch in Paris on October 20, 1918.

Lèvy, in 1919, tried to sell his American patent application to entrepreneur Emil Simon for $ 5,000. telling the skeptical Simon that Armstrong had stolen his idea.[36] Later that same year, he offered the rights to Le Materiel Tèlephonique, the French arm of Western Electric and, in this way, Lèvy's work came to the attention of AT&T's engineers. They, of course, had been working along the same lines for years but had evolved the superheterodyne principle so gradually that they essentially didn't know what they had.[22] Levy's patent seemed to cover the most practical form, so AT&T bought his American application for $ 20,000..[36]

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[32] Edwin H. Armstrong, "The Superheterodyne -- Its Origin, Development, and Some Recent Improvements," *Proc. I.R.E.* 12 (Oct. 1924), pp.539-552. Also, (with a different fig.1) *Radio Broadcast* 5 (July 1924), pp.198-207.

[33] Col. (later General) Gustave Ferriè (1868-1932) was an influential proponent of military radio, and his Eiffel Tower laboratory was at the center of new developments. *L'Onde Electrique* 11 (Feb. 1932), pp. 45-52).

[34] Corresponding foreign patents:
U.S. 1,734,038 applied Aug.12, 1918, issued Nov.5,1929
Britain 143,583 accepted June 3,1920
Germany 536,049 issued Oct.1, 1931

In accordance with international convention, these all had priority dates of Aug. 4, 1917.

[35] Gutton collaborated with Gen.Ferriè on short-wave studies in the 1920s, and later was director of the Laboratoire National de Radiòelectricite.

[36] Aitken, *The Continuous Wave* (Princeton, NJ: Princeton University Press, 1985), p.467.

LEVY WINS

Levy eventually formed his own company, Les Etablissements Radio L.L., which he headed for some years.[37] His superheterodyne patents were publicized in the magazine *Radioelectricite* in April and May 1921, but it was April of 1923 before he could advertise a superheterodyne broadcast receiver. As he explained in 1924, "The superheterodyne could not reach its ultimate capabilities in France on account of the government's slowness in expropriating the (German) Meissner patents covering the heterodyne and high-frequency amplifier coupling. Nonetheless, a model was built in 1919 which, at Paris with a 1-meter loop antenna, easily picked up boats in the Mediterranean."[38]

Radio L.L. produced three home models in 1923 and as the superheterodyne circuit became more and more popular, other companies joined in too. By the end of 1926, Levy had 65 French licensees.

In the United States (but not necessarily in France, at that time), two valid patents could not cover identical subject matter. Levy had filed first but, because his patent had a different purpose from Armstrong's and the claims were quite different, the patent examiner had apparently not noticed the conflict and had allowed Armstrong's patent to issue on June 8, 1920 (no. 1,342,885).

But Lèvy -- or AT&T -- noticed. Lèvy broadened his claims to purposely create an interference, by copying Armstrong's claims exactly. The Patent Office would then have to choose between the two inventors.

Now despite the indignant rantings of Armstrong's biographer Lawrence Lessing,[39] there was nothing sneaky or underhanded about Lèvy's procedure. Copying a rival's claims was in fact required by Patent Office rules, to remove any ambiguity over whether or not an interference existed. The only question was whether the invention that Lèvy originally disclosed, in 1917, would cover the new claims. The disclosure was not altered. After several years of legal wrangling, the Court of Appeals of the District of Columbia ruled that Lèvy's original disclosure would indeed support the new claims; in other words, all the features of Armstrong's superheterodyne were spelled out in Lèvy's description.[40]

Therefore, since Lèvy's filing date was seven months earlier than Armstrong's first date of conception, Lèvy was entitled to a patent and accordingly one was issued on November 5, 1929 (1,734,038) with a priority date of August 4, 1917. It incorporated seven of Armstrong's nine claims; the two remaining went to Alexanderson of GE, and Kendall of AT&T in similar fashion.[36]

While French patent procedure was fairly lax, the Germans were even more thorough than the Americans and a similar interference proceeding there resulted in a patent to Lèvy on October 1, 1931 (no. 536,049) again with a priority date of August 4, 1917.[41]

There were, in fact, a number of quasi-heterodyne systems invented earlier than either Armstrong's or Lèvy's. Walter Schottky, who was active in this field himself, listed three in 1926:[42]

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[37] 15 years, according to Champeix. Levy also ran his own broadcast station.

Champeix, "Qui a Invente le Superheterodyne?" *La Liaison des Transmissions* 116 (March - April 1979), 117 (April - May 1979).

[38] "Le superheterodyne Levy ne put atteindre tout le developpement dont il etait susceptible en France, 'a cause de la lenteur avec laquelle les services de l'Etat procedaient'a l'expropriation des brevets Meissner, dont l'emploi etait necessaire pour la realisation des heterodynes du super-heterodyne et pour la reglage facile de l'accrochage des amplificateurs 'a haute frequence.

Pourtant, malgre ces difficultes, un mod'ele fut cree en 1919, lequel permettait facilement a Paris sur cadre de l m. la reception des côtiers et bateaux de la Mediterranee.

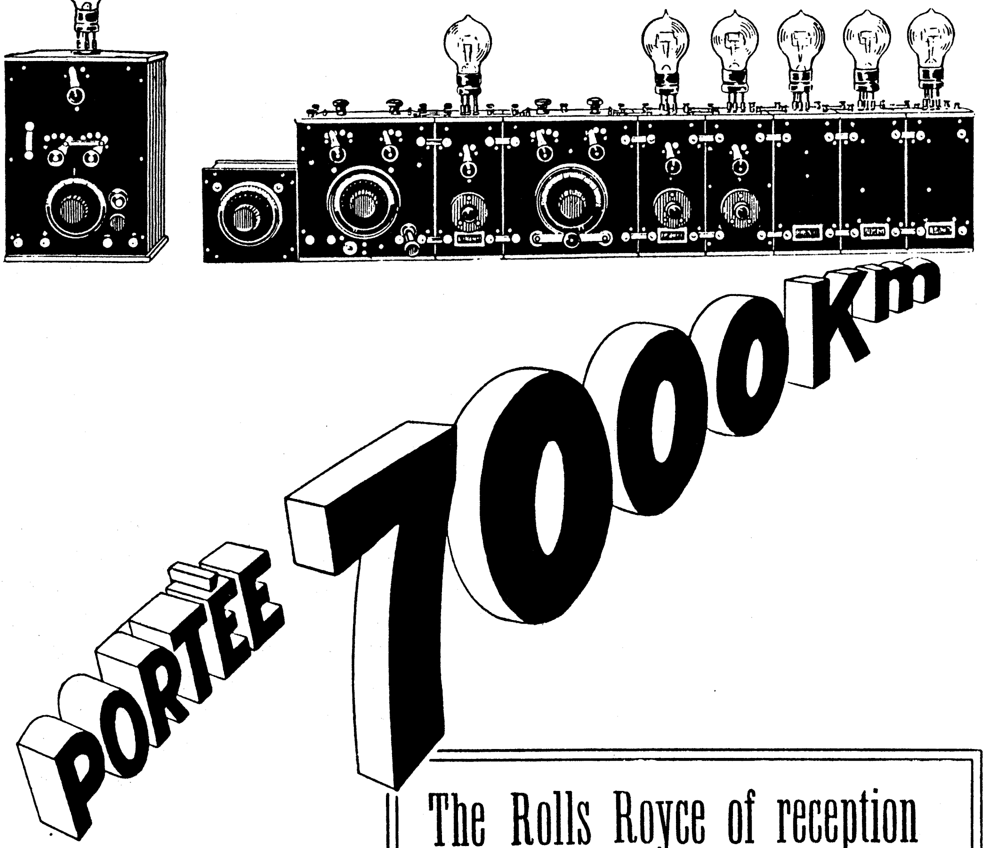
Lèvy, "L'Histoire du Super-Heterodyne," *Radio-Revue* 3 (Oct. 1924), pp. 186-188.

[39] Lessing, *Man of High Fidelity,* p.118/93. While Lessing is usually trustworthy, occasionally hero- worship gets the better of him. His statement here that the French government never allowed Lèvy's claims is absolutely false. And his description of Lèvy's patent and AT&T's conduct is, to say the least, misleading. Lessing also forgets to mention that Armstrong's superheterodyne patent was void after 1928. Champeix[37], after paraphrasing Lessing's account in his very thorough 1979 paper on the superheterodyne's invention, follows with a single sentence, "Voilà comment on 'ecrit l'histoire." (loosely, "See what passes for history".).

[40] 29F (2d)953. *Armstrong v. Levy*, decided Dec.3, 1928.

[41] Lèvy, "Au Sujet du Superhèterodyne," *L'Onde Electrique*[35] (May 1955), p.548.

❷ SUPERHÉTERODYNETTE (Brevet L. Lévy)



The Rolls Royce of reception

L'AUTORITÉ sans-filiste américaine la plus considérable a surnommé le SUPERHETERODYNE : *the Rolls Royce of reception*. Cette comparaison marque combien ce récepteur diffère de tous les systèmes récepteurs connus et à quel degré il les surpasse.

Le poste ci-dessus est une application complète du principe Superhétérodyne à l'AUDIONETTE.

C'est le seul appareil permettant de recevoir, à Paris, les postes anglais sur cadre de un mètre, en haut-parleur, en éliminant totalement toutes les émissions locales et toute perturbation parasite quelconque. Sur antenne, sa portée est illimitée.

PUB. PRATIQUE

E^TS RADIO-L.L

66, rue de l'Université, 66 - PARIS
GRAND CATALOGUE ILLUSTRÉ O, 1,50

Inventeurs-Constructeurs exclusifs
du " SUPERHÉTÉRODYNETTE "
et du " SUPERHÉTÉRODYNE"

L'ONDE ÉLECTRIQUE, April 1924

"The idea of employing the advantages of heterodyne reception for radio telephony also, by selecting an inaudibly high beat frequency, was probably published originally in 1913 by Mr. Hogan in the course of a discussion[8]. The idea of producing a beat frequency by means of a local source of oscillation, which was not intended to make the signals audible, but expressly to provide for another tuning and thereby increased selectivity, has been patented by Graf Arco and A. Meissner[9], and by H.J. Round[10]. Round's application also lays stress on providing inaudible beat frequencies, but actually offers no good selectivity against interference owing to the inherent necessary detuning of the aerial." [42]

8. Hogan, *Proceedings of the I.R.E.* 1, 97 (1913).

9. English Pat. 252, 1914, filed January 5, 1914 and D.R.P. 300896, January 15, 1917.

10. English Pat. 27,480, 1913, filed November 11, 1913.

A.M. Morse in The Electrician of July 31, 1925 also cited the equivalent British patents of the various contestants with much the same comments.[43]

LEVY LOSES

Even in France, the very birthplace of chauvinism,[44] the Frenchman Levy found it tough sledding to obtain public credit for his invention. RCA's 1924 publicity reached his country when *Radio-Revue* published a translation of Armstrong's 1924 I.R.E. paper in which, unlike the 1921 article, Levy's name did not even appear.

This oversight prompted a lengthy rebuttal by Levy in the same issue.[38] But Levy's struggles were not solely with Armstrong. In the popular weekly *L'Antenne,* a discussion began in late 1925 on the relative merits of the frequency-changing circuits used by the Lèvy and Ducretet companies. Lévy used a separate oscillator tube, and called his mixer tube a "detector," while Ducretet's engineers used a "bigrille" or double-grid tube for both functions and called theirs a "modulator".

By late 1925 Lèvy was beginning to sign up his competitors for royalty licenses to use his invention, and it is more than likely that Ducretet had commercial reasons for not admitting its circuit to be a superheterodyne. It is also more than likely that many others in the French radio industry felt similarly hostile toward Lèvy, since *L'Antenne* quickly became a forum for vituperative personal attacks on him, chiefly by the magazine's own editor, Henri Etienne. When'Etienne learned that another engineer attached to Ferriè's group during the war, Paul Laut had proposed most of what Lèvy had patented, in a memo written six months earlier, he reprinted the original memo and demanded that Lèvy explain himself. Lévy could only offer some weak excuses and "arguments specieux" and there the controversy rested, with his opponents having the last word.[45] Lèvy had his patent and, as Etienne put it, "filled his pockets" but, as late as 1955, had to write a bristling full-page reply to *L'Onde Electrique*, France's foremost electronics magazine, to correct a published story crediting Armstrong with the superheterodyne.[41]

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[42] Schottky, "On the Origin of the Super-Heterodyne Method, *Proc. I.R.E.* 14 (Oct. 1926), pp.695-698.

Hogan's comment, by the way, was an answer to "How do you receive radiotelephone signals with a heterodyne detector?" His reply was to keep the beat frequency inaudibly high. The "correct" answer, of course, is to zero-beat them with the local oscillator, which makes one wonder about the state of the art in those days! Hogan, it should be noted, was an extremely competent experimenter and engineer.

[43] Morse, "The Superheterodyne," *Electrician* 95 (July 31, 1925), p.121.

[44] Chauvinism: vainglorious or exaggerated patriotism, from Nicolas Chauvin, whose demonstrative patriotism and attachment to Napoleon came to be ridiculed by his comrades. (Webster).

[45] Champeix, "Qui a Inventè le Superhèterodyne?" (reference 37). Champeix met Paul Laut by accident in 1968 and heard the story from him, later reconstructing the affair from the published letters in *L'Antenne.* In the end, however, Champeix awards the laurel to Lèvy and Armstrong.

Laut contracted tuberculosis, and was sent away to the countryside to recuperate, for a year. He used his time to grapple with theoretical problems assigned by Ferriè, reporting his conclusions by letter. His superheterodyne proposal involved frequency-changing by the heterodyne, amplification at the intermediate frequency, and detection, but it did not include any IF tuning. Lèvy claimed in 1926, "Il me semble bien qu' à ce moment, la 'remarquable' petite note de M. Laut n'avait pas attirè outre mesure l'attention". ("It seems to me that, at that time, Mr. Laut's 'remarkable' short note did not attract much attention"), an opinion corroborated by his superior in a subsequent letter to *L'Antenne*. Laut stated in 1968 that, on his return to Paris in 1917, he was chagrined to learn that Lèvy had patented some of his ideas, but was told by Ferriè not to let personal considerations interfere with the war effort. Of course, it is a matter of record that Laüt did not contest Lévy's patent and, whatever he stated later (hindsight is always 20-20), he must have felt at the time that the matter was not worth pursuing. And in truth, Laut seems not to have gone much beyond what Round or Arco and Meissner had devised.

Levy always felt that Armstrong had stolen his invention, but there is no direct evidence for this.[46] Levy's ideas had indeed been publicized in military reports distributed to the American radio personnel; however the first such report had arrived before Armstrong was in Paris, and the second came after he had already done a good deal of experimental work and was preparing his patent application.

It is true that Armstrong, in his capacity as head of the radio research laboratory, was in close contact with French manufacturers, since inspection of incoming French equipment was being done at the same Paris location. And it was his job to keep abreast of French technical developments and to coordinate his group's research work with them.

Given Levy's emphasis on secrecy systems and selectivity, Armstrong probably felt that he had contributed little of novelty to the prior art, and only discovered the superheterodyne's potential after Armstrong pointed the way. Levy, conversely, knew that Armstrong did not deserve an all-encompassing patent, and he was stung by Armstrong's unwillingness to credit prior researchers in his 1924 paper ("It is unfortunate that Mr. Armstrong who, in his 1920 I.R.E. paper, had recognized our priority, has forgotten, in the midst of his glory, the source from which he drew.")[47]

I am grateful to Dr. Anders Widell (Lund, Sweden) for introducing me to Champeix' paper on Lèvy, to John M. Anderson of General Electric for searching that company's photographic archives, and to Joseph de Veer of the Marine Biological Library (Woods Hole, Mass.) for tracking down elusive references. Other contributors are credited under particular illustrations.

SUMMARY

Walter Schottky summed it up accurately in 1926:

" Finally, the aforementioned patent of Lucien Lèvy is of fundamental importance to the whole field; he must be considered, at least from the point of view of patent law, as the true originator of the super-heterodyne method, since the super-imposition of an adjacent frequency, an intermediate circuit tuned to inaudible frequencies, and a further rectification in order to convert into the desired signal, are described explicitly in his application (as one of several constructions).

"In regard to earlier existent publication, there may be a doubt as to whether the information would have brought about the desired technical progress we owe to the super-heterodyne method, as conceived by Mr. Armstrong and also described in the German application. After all, the actual aim of the high-frequency transformation or super-heterodyning principle consists in providing a suitable and relatively convenient radio-frequency amplifier for short waves, whereas the selectivity effects that Lèvy solely had in view are less important, according to the above considerations, and might be obtained as well by the use of a slightly-attenuated or reaction-coupled radio-frequency syntonizing circuit. The drawings of this application also leave it doubtful whether the elimination of the square-law rectifying action, which is so essential for the commercial use of the apparatus, would have been obtained by means of experimental sets constructed on the principle indicated in the application.

"The "word" seems, at any rate, to have been far less important than the "deed," and there appears to be no doubt that it is Mr. Armstrong and his collaborators to whom we owe the deed, which has made the super-heterodyne method such an invaluable instrumentality in radio engineering."[42]

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[46] As Champeix points out, Laut had good reason to feel the same way about Levy !

[47] "On pourra enfin regretter que M. Armstrong, qui avait, dans sa première communication a' la Societe' des Radio Engineers de New-York, vers 1920, reconnu notre anteriorite, alt oublie' au sein de sa gloire, la source a' laquelle il etait venu puiser." (*Radio-Revue*, reference 38). When the same material was reprinted, with additions, in a 1926 book on the superheterodyne, cooler heads prevailed and the phrase "au sein de sa gloire" was omitted.

Hemardinquer, *La Superheterodyne et la Superreaction* (Paris: Etienne Chiron, 1926).

ON THE ORIGIN OF THE SUPER-HETERODYNE METHOD

by **Walter Schottky**
Siemens Zentrallaboratorium du Wernerwerk, Germany

Originally published in *Proceedings of the IRE*, Vol. 14, no. 5, 695 - 698, Oct. 1926.

Mr. E. H. Armstrong recently explained in the *Journal*[1] that the idea of the receiving method named by him "Super-Heterodyne Reception" first occurred to him as a solution of the requirements of a war problem, and that in the course of further investigations, and due to various suggestions for improvements, this idea resulted in the excellent broadcasting receiving set that we admire so much today.

As interchange of views and, consequently, uniformity of scientific and technical development have now apparently been re-established to a large extent between the enemy countries, you will no doubt allow me to give a short outline of how and when the corresponding idea took shape in Germany.

It was a special and relatively unimportant war problem, namely wireless remote control, which claimed the collaboration of the Siemens Laboratory -- whose experiments were in part managed by me -- in the course of 1917[2].

As in the case of the problem mentioned by Mr. Armstrong, discrimination against waves of other frequencies and atmospheric disturbances was the dominant aim, and thus led to theoretical investigations relating to the selectivity problem of radio reception in general. The most obvious suggestion of improvement consisted in modulating the transmitted high frequency by means of a lower one, and in providing a corresponding double-tuned receiving set -- a suggestion which, as we now know, was the chief claim of Lucien Levy's patent application, filed in the summer of 1917[3].

An exhaustive investigation which I made in December 1917, of the advantages that might be gained by this method as applied to transmitting and receiving sets showed, however, that these would not altogether fulfill our immediate expectations. Under the most varying conditions possible, I compared the effects which an impulse (*i.e.* a sudden alteration of the electric field intensity) or a non-modulated radio frequency signal would produce in the terminal set, with the effect of the signal to which the receiving set was intended to respond; and I established the fact that insensibility to impulse disturbances is, to a large extent, *only dependent on the ratio of the period*[4] *required for the terminal signal, to the period inherent to the (most rapid) radio frequency cycle employed.*

Only in the case of interference due to non-modulated radio frequency signals lasting longer than about one-third of the mean frequency cycle, did a correspondingly reduced sensitivity result, compared with a simple receiving *circuit* tuned to this interfering frequency. Furthermore, the ratio of interference to signal sensitivity was chosen to be dependent on whether the rectification of the mean frequency followed a linear law or, (as in the case of weak signals in ordinary detectors and rectifiers) a square law; it was shown that the square law rectifying action prejudicially affected the ratio of interference sensitivity to signal sensitivity.

For this reason, and on account of the well-known loss in amplification which cannot be avoided with weak signals under square-law rectification, I considered the possibility of amplifying, by means of a non-selective radio frequency amplifier, the two adjacent frequencies Υ_1 and Υ_2 contained in the modulated carrier wave, to such an extent before their passage through the first rectifier, that the rectifying action would become approximately linear. But here I encountered a problem, the general importance and difficulties of which were already familiar to me, and which I had at first hoped to solve by the construction of special amplifying valves having large electronic currents and small internal resistance[5].

My acquaintance with the idea of inaudibly-modulated carrier frequency presented me (at the end of February and beginning of March) with a new solution, viz: that the incoming high frequency (at the frequencies Υ_1 and Υ_2 or, in the case of non-modulated high frequency transmission, at frequency Υ) could be converted linearly like ordinary heterodyne reception -- into a lower frequency wave which could be easily amplified, by causing the first receiver valve to oscillate at a frequency which would give inaudible beats when receiving the incoming frequency. In order to obtain the linear conversion of the wave, the amplitude of this auxiliary oscillation should be dimensioned in such a manner that it entirely *controlled the super-heterodyne valve over about one-half of its characteristic.*

It was by no means difficult to recognize the importance of this method, which actually represents the super-heterodyne principle, for all purposes of radio reception. In fact, the following entry was made by me in the journal of the K=Laboratorium for the period February 25 to March 16, 1918:

"A Frequency Transformation for Radio Reception

> "As the amplification of very short waves in many cases involves a large consumption of energy in the amplifier valves employed, it is of advantage to be able to convert short waves at the reception, without any loss of energy, into longer, similarly inaudible waves and then to amplify these only. This is accomplished by heterodyning another frequency differing by about 10% so that the beat-wave again becomes high frequency, but longer. Of special importance for radio telephony in which heterodyning is not possible."

The German patent for this method was filed on the 18th June, 1918[6]; since I could not myself draw it up nor pursue the matter further, it did not, unfortunately, assume the form I should have wished. Nevertheless, it emphasis the essential features of the super-heterodyne method and, thanks to the Nolan Act, patents have been granted in America and England, so that according to the present state of patent law in these countries as well as Germany, the manufacture of at least such heterodyne sets as permit the *amplification* of the transformed (inaudible) high frequency, is involved in the possession or right of utilization of this patent.

I should like to conclude this little historical note by referring to some still earlier publications and patent applications in our field[7], which are of historical importance in relation to the super-heterodyne idea, but were, probably, as unknown to Mr. Armstrong as to me. The idea of employing the advantages of heterodyne reception for radio telephony also, by selecting an inaudibly high beat frequency, was probably published originally in 1913 by Mr. Hogan in the course of a discussion[8].

The idea of producing a beat frequency by means of a local source of oscillation, which was not intended to make the signals audible, but expressly to provide for another tuning and thereby increased selectivity, has been patented by Graf Arco and A. Meissner[9], and by H. J. Round[10]; Round's application also lays stress on providing inaudible beat frequencies, but actually offers no good selectivity against interference owing to the inherent necessary detuning of the aerial.

Finally, the aforementioned patent of Lucien Levy[11] is of fundamental importance to the whole field; he must be considered, at least from the point of view of patent law, as the true originator of the super-heterodyne method, since the superimposition of an adjacent frequency, an intermediate circuit tuned to inaudible frequencies, and a further rectification in order to convert into the desired signal, are described explicitly in his application (as one of several constructions).

In regard to earlier existent publication, there may be a doubt as to whether the information would have brought about the desired technical progress we owe to the super-heterodyne method, as conceived by Mr. Armstrong and also described in the German application. After all, the actual aim of the high-frequency transformation or super-heterodyning principle consists in providing a suitable and relatively convenient radio frequency amplifier for short waves, whereas the selectivity effects that Levy solely had in view are less important, according to the above considerations, and might be obtained as well by the use of a slightly attenuated or reaction-coupled radio frequency syntonizing circuit. The drawings of this application also leave it doubtful whether the elimination of the square-law rectifying action, which is so essential for the commercial use of the apparatus, would have been obtained by means of experimental sets constructed on the principle indicated in the application.

The "word" seems, at any rate, to have been far less important in this field than the "deed," and there appears to be no doubt that it is Mr. Armstrong and his collaborators to whom we owe the deed, which has made the super-heterodyne method such an invaluable instrumentality in radio engineering.

REFERENCES

[1] The Super-Heterodyne, Its Origin, Development and Some Recent Improvements, *Proceedings of the IRE*, Vol. 12, no. 5, pp. 539 - 552. October, 1924.

[2] The Zentrallaboratorium of the Wernerwerk, known at that time as "Schwachstromkabel (K-) Laboratorium."

[3] English Pat. 143583 dated August 4, 1917. See also B. F. Meissner, *Radio Dynamics* 145-149, New York, 1916.

[4] Where mechanical relays are operated, the period of the terminal signal may be the natural oscillation of the armature; in the case of telephonic signals -- the cycle of the highest frequency that can be transmitted.

[5] D. R. P. 366829, filed November 11, 1917.

[6] D. R. P. 368937; English Pat. 135177, appl. 1502093. The first patent E. H. Armstrong is dated 30th December 1918.

[7] See also the report of J. H. More, *Electrician*, 1925, p. 121.

[8] Hogan, *Proceedings of the IRE*, Vol. 1, no. 3, pp. 97 - 102. July 1913

[9] English Pat. 252,1914, filed January 5, 1914 and D. R. P. 300896, January 15, 1917.

[10] English Pat. 27480, filed November 11, 1913.

[11] English Pat. 143583, date of appl. April 8, 1917.

AU SUJET DU SUPERHÉTÉRODYNE

A la suite de la notice nécrologique sur la vie et l'œuvre du Major Edwin H. ARMSTRONG, que l'un de nos membres, M. P. BRAILLARD, avait bien voulu préparer, et qui a paru dans le numéro de décembre 1954 de l'Onde Electrique, nous avons reçu, de M. L. LEVY, la lettre suivante, que nous nous empressons de publier :

RECTIFICATIONS SUR LA VIE & L'ŒUVRE DU MAJOR Edwin H. ARMSTRONG

PAR

Lucien LEVY

Inventeur du Superhétérodyne

Dans une note relative au regretté E. H. ARMSTRONG, note parue dans le n° 333 de décembre 1954 de l'*Onde Electrique*, l'auteur, M. P. B. lui attribue, sans preuves, mais d'une façon réitérée, l'invention du Superhétérodyne.

Si, en général, je m'associe à l'hommage rendu à l'œuvre de premier ordre d'ARMSTRONG, je crois que cette œuvre est suffisamment considérable pour qu'il ne soit pas nécessaire d'y ajouter, sans motif valable, l'invention du Superhétérodyne.

Qu'ARMSTRONG ait apporté au développement et à la propagande du Superhétérodyne l'appui de sa personnalité, de son dynamisme, de son enthousiasme, cela est certainement vrai ; qu'il en ait conçu ou réalisé l'invention le premier, c'est absolument inexact.

Conformément au bon sens, à la Loi française et aux Conventions Internationales, seul, le premier inventeur peut revendiquer une invention. Or, il n'y a pas le moindre doute qu'ARMSTRONG n'a aucun droit à cette revendication.

Lorsqu'il déposait en France, le 30 décembre 1918, son premier brevet 501.511 sur le Superhétérodyne, j'avais déjà déposé sur cette invention deux brevets (493.660 du 4 août 1917 et 506.297, du 1^{er} octobre 1918), et j'avais déjà réalisé le premier récepteur Superhétérodyne.

De plus, mon invention et sa réalisation avaient été diffusées et publiées (notamment par ma note polycopiée du 20 octobre 1918) dans les Services de la Radiotélégraphie Militaire auxquels j'appartenais comme Officier, et auprès desquels le Major ARMSTRONG était détaché. Je possède encore quelques exemplaires de cette note, qui était honorée d'une déclaration du Général FERRIÉ. En ce temps là, la *Radio Française*, que le Général incarnait, avait la fierté de ses inventions.

Il résulte de la publication de ma note du 20 octobre 1918, que le brevet d'ARMSTRONG du 30 décembre 1918, sur le Superhétérodyne, était non seulement antériorisé, mais, légalement, absolument nul.

Postérieurement à mon brevet de 1917 et antérieurement à ARMSTRONG, un autre inventeur bien connu, SCHOTTKY, avait d'ailleurs également déposé en juin 1918, en Allemagne, un brevet sur le Superhétérodyne, qui eut antériorisé celui d'ARMSTRONG, si le mien n'y eut suffi.

En ce qui concerne l'interférence entre les brevets américains ARMSTRONG et LEVY, j'estime, contrairement à la note de M. P. B., qu'il est important, pour l'histoire de l'origine du Superhétérodyne, de connaître le résultat de la procédure devant le Patent-Office.

C'est pourquoi je crois nécessaire de fournir sur cette interférence, les renseignements qui manquaient, semble-t-il, à M. P. B., pour éclairer son opinion, puisque l'existence de mon brevet de 1917, qu'il a bien voulu indiquer dans sa note, n'y suffisait pas.

Qu'un pool de brevets ait été constitué ou non, entre différentes Sociétés américaines, cela ne concernait que les intérêts matériels de celles-ci, mais ne réglait nullement la question de la détermination du premier inventeur, le seul qui soit le véritable inventeur, celui auquel est dû le crédit moral de l'invention (en l'espèce le Superhétérodyne).

Or, l'interférence entre les brevets d'ARMSTRONG et de LEVY, après un litige de plusieurs années devant le Patent-Office, a été résolue, par décision du 3 décembre 1928 de la Cour d'Appel du district de Colombia, en faveur du brevet L. LEVY, dont la priorité d'invention a été reconnue.

Le brevet U. S. a été délivré le 5 novembre 1929 à L. LEVY et à son cessionnaire, l'*American Telegraph and Telephon C^o*, sous le n° 1.734.038, avec priorité du 4 août 1917.

D'ailleurs ARMSTRONG, dans sa première communication sur le Superhétérodyne, publiée dans les Proceedings de l'*Institute of Radio Engineers*, de février 1921, et SCHOTTKY, dans un article des mêmes P.I.R.E. d'octobre 1926, avaient tous deux reconnu mon antériorité.

SCHOTTKY ajoutait « La patente de Lucien LEVY est d'importance fondamentale, pour tout le domaine, il doit être considéré, au moins au point de vue de la Loi des brevets, comme le véritable inventeur du Superhétérodyne ».

Enfin, le patentamt allemand, après un long examen de la demande de brevet L. LEVY, et malgré des oppositions acharnées, a reconnu la valeur de l'invention qui y était revendiquée.

Le brevet allemand a été accordé le 1^{er} octobre 1931, sous le n° 536.049 avec priorité du 4 août 1917 à la Société *Telefunken* cessionnaire de la demande L. LEVY.

La première des douze revendications accordées est très large. Elle vise « le procédé de réception et d'amplification pour télégraphie et téléphonie sans fil, caractérisé par le fait que, après transformation de la fréquence de réception en une fréquence locale ultra acoustique, l'énergie de cette nouvelle fréquence est ampliée ».

C'est là l'invention même du Superhétérodyne sous sa forme la plus générale, invention reconnue nouvelle et valable sur la base du brevet français L. LEVY, du 4 août 1917.

Dans ces conditions, l'affirmation qu'ARMSTRONG aurait inventé le Superhétérodyne, est non seulement contraire à la réalité, mais encore dénuée de toute base légale. Pour propager une pareille légende il faut ignorer les faits et les dates, ou négliger toute logique et toute vraisemblance.

Il faut s'y résigner : le Superhétérodyne est une invention française, qui ne peut, ni ne doit être méconnue dans son propre pays.

Cette question étant maintenant réglée, et compte tenu des observations présentées ci-dessus, lesquelles modifient d'ailleurs radicalement la note de M. P. B. sur ce point important, on doit savoir gré à celui-ci d'avoir rappelé les services rendus par l'un des pionniers qui ont établi les bases du prodigieux développement actuel de la radio-électricité et montré la condition toujours difficile, souvent injuste et quelquefois tragique, des inventeurs indépendants.

Qu'il me soit permis, en évoquant avec émotion le souvenir d'E. H. ARMSTRONG, que j'ai connu vers la fin de la guerre de 1914, de regretter vivement la perte, pour l'humanité et la radio, d'un esprit aussi original et d'une aussi grande valeur que le sien.

Imprimerie Marcel Bon, Vesoul. — Dépôt légal : 2^e trimestre 1955. — I. n° 25. — 4.900. 578 E. n° 20. — La gérante : Mme Chiron.

(Translation from the French)

ON THE SUBJECT OF THE SUPERHETERODYNE

Pursuant to the obituary about the life and work of Major Edwin H. ASRMSTRONG, that one of our members, M. P. Braillard, kindly prepared and which appeared in the December 1954 issue of l'Onde Electrique, we have received, from M. L. Levy, the following letter, that we are pleased to publish:

CORRECTIONS CONCERNING THE LIFE & WORKS OF MAJOR EDWIN H. ARMSTRONG

by

Lucien Levy
Inventor of the Superheterodyne

In a note concerning the late **E. H. Armstrong,** in the issue no. 333 of December 1954 of *l'Onde Electrique*, the author, M.P.B. attributes to him repeatedly, but without proof, the invention of the Superheterodyne.

If, in general, I join in the homage rendered to the works of the highest order of Armstrong, I believe that his work is of sufficient significance that it is not necessary to add to it, without justification, the invention of the Superheterodyne.

That Armstrong contributed much to the development and publicizing of the Superheterodyne by virtue of his personality, dynamism, and enthusiasm is certainly true; that he conceived or realized the invention first, is absolutely incorrect.

Conforming to common sense, French Law, and International Conventions, only the first inventor may claim an invention. Thus there is no doubt that Armstrong has no right to such a claim.

When he applied in France, on 30 December 1918, for his first patent 501,511 on the Superheterodyne, I had already filed two patent applications upon that invention (493,660 of 4 August 1917 and 506,297 of 1 October 1918), and I had already built the first Superheterodyne receiver.

Moreover, my invention and prototype had been publicized (notably by my duplicated note of 20 October 1918) in the Services of Military Radiotelegraphy of which I was an Officer, and to which Major **Armstrong** was attached. I still have several copies of this note, which was honored by a proclamation of General **Ferrie.** At the time, *Radio Francaise*, that the General personified, supported pride in one's inventions.

The result of the publication of my note of 20 October 1918 was that the Armstrong patent of 30 December 1918 on the Superheterodyne was not only predated but, legally, absolutely voided.

After my patent of 1917 and before that of Armstrong, another well-known inventor, Schottky, filed a patent upon the Superheterodyne in June 1918, in Germany. This would have predated Armstrong's if mine did not suffice.

Concerning the interference between the American patents of Armstrong and Levy, I believe, contrary to the note of M. P. B., that it is important for the history of the origin of the Superheterodyne to understand the results of the procedures before the Patent Office.

That is why I find it necessary to furnish, in the matter of this interference, information which M. P.B. lacked in declaring his opinion, since the acknowledging of my patent of 1917 in his note, did not suffice.

That a pool of patents was or was not constituted between different American corporations is of concern only to their material interests, but in no way nullifies the question of the determination of the first inventor, the only one who can be considered the true inventor, to whom is morally due the credit of the invention (of the Superheterodyne circuit).

Thus, the interference between the patents of Armstrong and of Levy, after the litigation of many years before the Patent Office, was resolved by the decision of 3 December 1928 of the Court of Appeals of the District of Columbia, in favor of the L. Levy patent, by which the priority of the invention was recognized.

The U.S. patent was granted 5 November 1929 to L. Levy and to his licensee, the American Telegraph and Telephone Company, under the number 1,734,038, with priority to 4 August 1917.

Furthermore Armstrong, giving the first public announcement of the Superheterodyne in the *Proceedings of the Institute of Radio Engineers* of February 1921, and Schottky, with an article of the same *P.I.R.E.* of October 1926, both recognize my priority.

Schottky added "The patent of Lucien Levy is of fundamental importance for the whole field, he should be considered, at least from the point of view of the patent Law, as the true inventor of the Superheterodyne."

Finally, the German patent office, after a long examination of the claims of the patent of L. Levy, and in spite of strong opposition, recognized the validity of the invention which was therein claimed.

The German patent was issued 1 October 1931 under the number 536,049 with priority to 4 August 1917, to the Telefunken company, assignee of the application of L. Levy.

The first of twelve claims awarded is very large. It covers "the procedure of amplified reception of wireless telegraphy or telephony, characterized by the fact that, after conversion of the received frequency with a local ultra-sonic frequency, the energy of the new frequency is amplified."

This is the same Superheterodyne invention in its most generalized form, an invention recognized as new and valid based upon the French patent of L. Levy, of 4 August 1917.

Under these conditions, the claim that Armstrong had invented the Superheterodyne is not only contrary to reality, but also without any legal basis. To propagate a similar legend is to ignore the facts and the dates, or neglect all logic and all probability.

One needs to resign himself: the Superheterodyne is a French invention that cannot, nor should not go unrecognized in its own country.

While this question will henceforth be ruled and measured by the observations presented above and which otherwise radically modifies the note of M. P.B. on this important point, one should know and be grateful for his reminding us of the services rendered by one of the pioneers who established the bases of the current prodigious developments of radio-electricity and for showing the always difficult conditions, not infrequently tragic, of independent inventors.

If I may be permitted, in remembering with emotion the memory of E. H. Armstrong whom I knew towards the end of the war of 1914, of deeply regretting the loss to humanity and to radio of a spirit as original and of as great value as that of his.

PROBABLY A WHOLE LOT MORE THAN YOU EVER WANTED TO KNOW ABOUT THE SUPERHETERODYNE RECEIVER

by **Ed Lyon**

Originally published in the Major Armstrong Memorial Amateur Radio Club *Newsletter* (Jan. - May 1987)

Of all the radio circuit inventions, none, save the vacuum tube itself, has had the far reaching utility of the superheterodyne circuit. Found in virtually every radio receiver, television set, and radar built since 1930, it has enabled communicators to open up the frequency spectrum to the region at and above that of visible light. The former limit of a few "Megacycles" would still be with us without this simple but profound technique of converting the high frequencies down to a manageable band within the receiver.

The way Major Edwin Howard Armstrong tells it, the idea of the superheterodyne receiver circuit hit him one night in France during the Great War. It was a time when he and his assistants were striving to detect the approach of enemy aircraft by listening on radio receivers for the telltale purr of the aircraft's engine spark plug discharge. Today we would say Armstrong was engaged in ELINT, Electronic Intelligence. His problem in detecting the feeble engine noise signals amongst the clatter of high-power spark transmitter signaling surrounding him seemed formidable. He, like others before him, felt that the better detection hunting grounds were at frequencies of one megahertz and above. Unfortunately, radio receivers were abysmally insensitive at these frequencies. The deForest audions of the time were still of the "soft" variety, what we today would discard as gassy tubes, and weren't useful above about one megahertz. The "hard" tubes of GE, Westinghouse, and Western Electric were better, but their low transconductance values, coupled with their high interelectrode capacitances, made them also run out of steam at these frequencies.

It was well known at the time that these same tubes could perform quite well at frequencies down in the 100-kilohertz region, and so the crux of the Major's invention was the conversion of the high incoming signal frequency down to a readily amplified low frequency, say around 40 to 100 kilohertz. Then, amplification could be applied and the signal, now at the new lower frequency, could be routed through the usual detection and audio amplification stages of radio reception. The Major made it clear that his invention was the conversion process (heterodyning) from the high frequency down to the low but super-audible frequency.

Armstrong called his conversion step "heterodyne detection," as he thought that this "detector" stage actually stripped the audio signal from the original high-frequency carrier and, in its place, slipped the new heterodyned (intermediate) frequency under the audio. To preserve the audio signal fidelity as it changed its carrier frequency, it was important to Armstrong that the new carrier (the intermediate frequency) be much higher than the highest audio frequency expected.

Except for this intermediate frequency criterion, Armstrong's conversion step was identical to the earlier heterodyne reception process attributed to Reginald Fessenden who had discovered, exploited, and patented the heterodyne effect in continuous-wave reception. The effect, of course, is the same as had been evident to piano tuners as early as the 16th century, namely, the production of the "beat note" as a result of two tones simultaneously striking the ear, the beat note frequency being the difference between the two original notes' frequencies. Fessenden had heard the audible tones produced any time two or more very closely tuned continuous-wave radio transmitters' signals were simultaneously received. He reasoned that the pleasing tones produced meant that he didn't have to tone-modulate his continuous-wave transmitters to make them easily "readable"; he simply had to couple the outputs of tiny auxiliary transmitters into each receiver. By tuning these "local oscillators" to very nearly the same frequencies as those of the signals sought, the Morse keying on the desired transmissions came out as clear tones. Not only were the Morse signals easier to copy this way but they could be read through a myriad of other signals, a tribute to the remarkable filtering capability of human hearing.

Armstrong had been exposed to Fessenden's heterodyne reception method (using, first, little Poulsen arc generators, then the vacuum tube oscillators) throughout his World War exploits, and undoubtedly this nearly standardized reception scheme played a part in his invention. But there were other heterodyne ideas floating around in France in WWI. A French radioman, Lucien Levy, had worked out a scheme for facilitating the reception of signals transmitted at frequencies as high as 2 or 3 MHz, considered too high for the tubes of the day. He transmitted two signals, one Morse keyed and the other unkeyed (continuously ON). These two signals were very close together in frequency, say, one kilohertz apart and, upon reception, the signals passed through a single tuned circuit (tuned to the 2 to 3 MHz signals), thence directly to a detector where the beat note emerged, as in Fessenden's method. The only difference was that Levy's "local oscillator" wasn't very local. There is very good reason to believe that Armstrong also had access to Levy's invention, and witnessed its operation in the field, this according to the postwar report to the Secretary of War by the Army's Chief Signal Officer, Major General George O. Squier.

In addition to these two true heterodyne systems used in WWI, to which Major Armstrong had access before he invented the superhet circuit, there was a near-superhet circuit amongst the many schemes he tested in the field in France. In this circuit, by the Hammond Laboratories' B.F. Miessner and J.H. Hammond, Jr., tone-modulated Morse signals are transmitted, say, from an interrupted-spark transmitter. At the receiver, a first tuned circuit is set on the frequency of the transmitted carrier, say, one MHz. Then crystal (or audion) detection occurs, followed by further tuned amplification, where the tuned circuits are set to the tone (spark interruption) frequency which, Hammond points out, may be super-audible. Then crystal, audion, or heterodyne detection is imposed again, the Morse clicks (or tones, if final heterodyne detection was used) are audio amplified, or sent to the output. So Hammond's scheme called for cascaded tuned circuits at differing frequencies, with detection interposed between. Many years later, Hammond (with E.S. Purington) would write an article for the *Proceedings of the IRE* (Sept. 1957) in which he would allow that his circuit was practically a superhet, and that he should get full credit for the superhet's invention.

This Hammond/Meissner circuit was used during the war for enhancing the ability to receive signals in the presence of intense jamming by enemy spark transmissions, and we know that Armstrong had a part in the testing of this and other Hammond Laboratories methods for anti-jam reception and anti- intercept transmission.

It is impossible to tell how much, if any, influence these three earlier techniques, Fessenden's heterodyne, Levy's dual-transmitted-frequency heterodyne, and Hammond's cascaded-frequency receiver had upon Major Armstrong's thinking while he pondered the problem of detecting the feeble aircraft engine emissions in France. Certainly all the ingredients of a superheterodyne circuit were there in those three systems. But the essence of invention is the matching of a problem and a novel solution, no matter in which order they are realized. And to Armstrong must go the credit for discovering the utility of the superhet, the ability to reduce any incoming signal frequency to an easily amplified and filtered common frequency through the use of a heterodyne circuit and local oscillator. The courts agreed that Armstrong was the inventor, too, for a while. And he needed to have only a temporary hold on the idea, at that, for by 1920 Armstrong had sold his rights to this and two other important patents to Westinghouse. And we all know the story from there. In 1921 the radio division of Westinghouse, patents and all, went into the RCA group, and then Sarnoff owned the superhet circuit.

For a while there was no pressure on Sarnoff to try to market the circuit. It seemed wasteful of tubes, requiring a local oscillator and a "heterodyne detector" in addition to the usual complement of tubes. He was doing all right so far, exploiting the Armstrong regenerative circuit, which extracted so much amplification from a single tube that he could drive a horn speaker using but two tubes in total, such as in the Radiola III. His was a drive to get radios out to the public at minimum operating costs such as for batteries and tubes. But two events changed his mind, and sent him scurrying for Al Goldsmith, his chief development engineer, and then for Armstrong to help Goldsmith. First was the sudden and unprecedented success of Hazeltine's Neutrodyne radio receiver, the first three-dialer that even Mother could operate. This receiver was manufactured with a certain degree of controlled scarcity to keep the public yearning, and it put real market pressure on RCA who was having trouble getting the bugs out of the GE and Westinghouse production lines. Second was the development, with no fanfare, of a superheterodyne receiver by the telephone company (Western Electric).

Western Electric (WE) had the distinction of being one of the most decorated firms to have served the armed forces during the Great War, and deservedly so. Their engineers were at the front, in the rear echelon repair depots, in the supply lines, and in the WE factories, day and night, churning out superb equipment for the war effort. And at very little pay. The folks back home subsidized most of it through their telephone bills. At the front, WE had easy access to all the competitive circuits and ideas being tried by the Allies in much the same way Armstrong did. WE even had access to Armstrong's tests and his results, even though the phone company alleged that Armstrong had had access to WE's ideas in Brooklyn, before the war.

It has been noted by the late Lloyd Espenschied, long the telephone company's historian, that WE and Bell Labs' engineers worked with L'evy and another Frenchman, Marius Latour, on various heterodyne schemes, and it is Levy whom WE credits with the ideas that led to WE's first commercially successful broadcast superhet, the WE Model 4-A, in 1922. This radio was typical of WE equipment of that era (it was nearly unaffordable), using the military type N tubes, those so-called "peanut tubes." WE produced the radios only for commercial interests such as shipping lines, their own phone company, and broadcast stations. WE had been building successful, one-at-a-time superhet radios from 1919 to 1922 for wireless extensions of the Bell System, and telephone company engineers like Espenschied, Carson, Heising, and Englund had secured patents on many heterodyning circuits for signal multiplexing, sideband suppression, and static suppression in the wireless field. Many of these developments are duly reported in the 1920 - 1924 period in the *Proceedings of the IRE*, but what the phone company engineers missed was that the superhet circuit was a gem of an idea for the common consumer's radio.

But the event that shook Sarnoff's complacency occurred in October 1922, when the phone company took test reports on the Model 4-A receiver and the, a little later, a model receiver itself to Goldsmith for a little "show and tell." An amazed Goldsmith quickly brought in Sarnoff who also gaped at the beautiful set and at its performance. Sarnoff needed no further prodding. He immediately started plans to develop his own superhet based on the Armstrong patent. Not so amazingly, Armstrong's tuned-i.f. version of the superhet circuit and WE's look very much alike. (Armstrong's very first superhet used a resistance-coupled, untuned i.f. amplifier.) When Goldsmith ran into trouble with severe tuning circuit interaction (plus too darn many tubes to suit Sarnoff), he went to Sarnoff with a counter-plan to go a bit slower on the superhet, and to restart the production lines on the other Radiolas, all of which had slowed to the point that several generations were trickling to the marketplace together. Sarnoff disagreed, and sent for Armstrong and Houck. Lawrence Lessing, Armstrong's biographer, relates the story of how the Major saved the day by working round-the-clock with his faithful Houck to get the set to work well. What they would up with, the AR812, became the subject of a famous IRE paper by Armstrong, presented in March 1924, and published in the *Proceedings* in December 1924. This set hit the market in 1924, and was followed immediately by the same electronics in a console cabinet with built-in rotary loop antenna, the Radiola Super-VIII. To hold the superhet circuit for RCA alone, GE, the manufacturer, was tasked to hide the electronic circuitry in a metal-clad block of wax-like substance, the dreaded catacomb. To save tubes, Armstrong borrowed an idea from the David Grimes devotees, and reflexed two of the tubes, getting four stages from two tubes.

Armstrong claimed to be able to identify which stages were which in the reflexed section of the radio, but reference to the schematic will reveal that there are several ways the combination of two tubes could act as the local oscillator, and several ways of achieving the heterodyne process in the reflexed stages. The operating behavior of the AR812 shows this effect also. Stations with substantial field strengths can be found at four to eight distinct places on the dial, a problem that was considerably alleviated a couple of years later when Sarnoff built a deluxe model of the catacomb superhet, the Radiola 28, which un-reflexed the same stages, using an extravagant eight tubes, but now that socket-powered battery eliminators were becoming common, such a tube complement became less of a burden on the Customer's battery budget. The RCA catacomb superhets all used "second harmonic" local oscillators, Harry Houck's contribution to the development. These oscillators operated at half the required frequency, but the inevitable distortion which comes with the heterodyning stage generated the second harmonic of the local oscillator's signal, which was what was needed in the first place. The advantage, for the RCA circuit, was a reduction in the degree of tuning control interaction, the two controls being one for tuning the local oscillator and the other for selecting the incoming signal frequency.

During the period between Armstrong's first successful superheterodyne radio tests in 1918 - 1919 and the 1924 marketing of RCA's first superhet, the AR812, several notable superhet receivers saw service. These were, in general, sets made from kits designed by Armstrong licensees. (Westinghouse's agreement to purchase Armstrong's patents allowed the Major only to continue licensing amateur and experimenter suppliers to market kits.) One of the most successful such kit-designers was Charles Leutz. His circuit was virtually the same as Armstrong's early tuned i.f. one, quite naturally, as Leutz followed his Armstrong license to the letter. But Leutz called for the very best of components, being a firm believer that the worthwhile costs much more. He shunned any cheap reflex circuits, so that electrically his sets do not resemble the AR812 at all. He proudly called for all the tubes the set needed, in both his Model C and C-7. The C-7 even used Armstrong's regenerative detector stage, getting by with seven tubes, all one-ampere 201s. Leutz believed that anyone not willing to invest in a 100-ampere-hour A battery just wasn't serious about amateur radio.

The U.S. Navy was becoming a bit nervous about the general direction of Armstrong's developments. First, his regenerative detector, then his super-regenerative receiver, then his superheterodyne set, all tended to radiate signals, just like little transmitters. The Naval Research Laboratory had just been established, in 1923, to carry out the radio development work of both the Bureau of Steam Engineering and the Bureau of Standard's Aircraft Radio Laboratory, and they were striving to develop radio receivers that would not give away the fleet's location via the little signals inadvertently emitted from the receivers and intercepted by an alert enemy. Leutz recognized their problem and promptly came up with his Model C-10, a ten-tube beauty, which was but a C-7 with three stages of tuned radio frequency (TRF) amplification ahead of the C-7's heterodyne stage. The idea of all these TRF stages was simply to isolate the radiating local oscillator from the receiver's antenna circuit, thus cutting down the tendency of the local oscillator to emit via the receiver's antenna. This set became known as the "Admiralty" model, as a result of its adoption by the Navy.

So far we have seen two "Armstrong" designs, one following all the Armstrong details and built only for the real enthusiast by Charles Leutz (exemplified by his Model C), and one started by Al Goldsmith but adapted for the "mass market" by Armstrong and Houck themselves, exemplified by the RCA AR812 and Radiola VIII. From a supposedly different lineage the Western Electric Models 4-A and 4-B emerged somewhat ahead of Leutz's or RCA's sets, and these radios became standard background features in nearly every broadcast station in the country. There was a certain amount of rivalry at play between these two superhet families.

Armstrong read papers before the prestigious Radio Club of America and before the IRE meetings, describing his circuit, and in some of the early presentations he referred to the heterodyne stage as a "first detector," or rectifier. Curiously, his "first detector" nomenclature has persisted to this day. These concepts derived from his notion of how the heterodyne stage worked, stripping the program modulation off the original character and onto the new, i.f., carrier. But the erudite telephone company engineers, and many other radio engineers as well, pointed out that a special form of rectification or detection was far better than Armstrong's plain garden-variety rectification, and that was "square-law detection." They showed mathematically that it was the squaring of the sum of the two input signals (the desired signal to be received and the local oscillator signal) that produced output waves rich in the desired i.f. component.

Armstrong never argued with mathematics, even though he never relied on math unless he had to, and that only when he couldn't prove his point empirically. But he respected math, and conceded, then vigorously supported the square-law detection requirement. But there was another engineer who didn't like either concept -- linear rectification or square-law detection -- in the heterodyne stage. He was Robert E. Lacault, and he reasoned that the common heterodyne circuits of the day, whether Armstrong's or WE's, were both inefficient. He figured that both schemes simply added the incoming signal to the local oscillator signal, then subjected the sum to either linear or square-law rectification. He admitted that the square-law circuit was superior to the linear circuit, but he felt that if an incoming signal, A, and the local oscillator signal, B, were added, yielding $(A + B)$, then the square-law circuit performed the operation $(A + B) x (A + B)$, yielding $[A^2] + [2AB] + [B^2]$.

Lacault saw that these three terms (each in brackets above) represented three signal components: the second harmonic of the incoming signal, the product of the incoming signal and the local oscillator signal (times two), and the second harmonic of the local oscillator signal, respectively. Quite obviously, the first and last components had nothing to do with heterodyning, only with production of undesirable second harmonics, any of which could radiate to cause interference, or at least require further filtering to keep them out of the downstream receiver circuits. Only the second term produced any heterodyning, and of course many electrical engineers had gone through the mathematics describing the heterodyne process and all had concluded that it is the product of the last two mixing signals that produces the sum and difference output frequencies. The only redeeming merit to the touted square-law detector was that it produced, mathematically (and actually, too), somewhat more conversion gain, or heterodyne efficiency, than did the linear one.

Lacault then simply replaced the Armstrong heterodyne detector, or rectifier, with a multiplying circuit. Such circuits are not new to radio; they were called modulators, and were used in all broadcast transmitters to place the program signal on the radio- frequency carrier. With no Armstrong license, he carefully marketed kits of high quality which used his modulator circuit as the "first detector." These he called "Ultradynes," rather than superheterodynes, and he sold them through several East Coast jobbers, the largest of which was Phenix Radio. Typical of his version of the superhet is the Ultradyne L-2, an eight tube set whose first stage is the modulator. The incoming signal is tuned and presented to the grid of a triode, whose plate supply is the signal on the grid of the local oscillator tube, rather than a source of B+. Thus the output of this stage is proportional to the product of the input signal and the local oscillator signal. The L-2 easily outperforms, in sensitivity and ease of tuning, the Leutz C-7 or any catacomb Radiola. It does even better if the modulator (heterodyne) stage plate is connected to the local oscillator plate instead of the grid, affording the modulator a tad more amplification.

So long as the only superhet radios on the market, aside from the Radiolas, were "enthusiast" sets, made from kits or in custom configurations, one at a time, Sarnoff was happy. Everyone who published a radio magazine ran article upon article on various forms of the superhet circuit, and all these served to increase the circuit's popularity. The radio amateurs were in the process of discovering the short-wave bands that the Navy had been testing since 1918 for their long-haul capabilities, and those hams who experimented in those frequencies found the superhet a miracle circuit. All long-range radio records fell to these hams in their sometimes casual tests across oceans and continents. Marconi's theory that the longer the path the longer the required wavelength was being scoffed at regularly, and these factors drove the Navy even faster to lay claim to the frequencies above the broadcast band. But the hams were there, and there, at least in restricted areas, they stayed.

Some of the circuits developed in these early days of commercial superhet circuits (1924 - 1926) were very mild modifications of Armstrong's original or Leutz's improved sets, but some were significantly improved. Lacault's Ultradyne we have already looked at, and the journals of the day featured new circuits in every issue. One of note was the Tropadyne, by Clyde Fitch, which used but six tubes. The local oscillator served as the first "detector" as well, and to keep the local oscillator signal from getting out of the set via the antenna circuit, a somewhat balanced local oscillator tuned circuit was employed, with the antenna circuit feeding the midpoint of the local oscillator tuned circuit. Pressley, of the Army Signal Corps, further improved this circuit by adding a balanced tuning capacitor along with a balanced coil, keeping operator hand capacity from detuning the set. He termed his circuit a Wheatstone Bridge circuit, to emphasize its balanced, non-radiating nature.

But these efforts were helpful to RCA, and not a threat, so long as the number of sets involved were small. Sarnoff, meanwhile, was pressing his GE production line for more superhets, while at the same time he put pressure on Westinghouse, his producer not heavily taxed to worry about superhets, to get their research on socket-powered sets concluded. Westinghouse was RCA's leader in both in-house socket-powered battery eliminators and in the development of true a.c.-powered vacuum tubes, and the successful combining of the GE superheterodyne with a Westinghouse-type socket-powered set was Sarnoff's dream. The RCA Radiola 60 was the result, a very popular, but expensive, all-triode superhet which is still very popular among collectors today. Technically, it was not very much better than the Radiolas 17 or 18, which were all-triode TRF sets made for the a.c. power line. But at least the Radiola 60 design had solved the old two-dial interaction and radiation problems of the catacomb superhets. It was a milestone in the superhet saga, a one-dial radio anyone could operate.

By this time, the end of the '20s, many dire economic problems faced radio industrialists in America, aside from the impending worldwide depression. It was becoming universally recognized that the superheterodyne radio was the key to good home receivers at modest costs, what with the then-current development of the tetrode and pentode tubes and the proliferation of socket-powered circuits. But with RCA holding back all considerations of licensing the superhet design, other radio manufacturers were hurting. RCA's true superhet monopoly was beginning to create pressures of great magnitude. Many small manufacturers simply bootlegged the sets, and were eventually chased, caught, or at least kept off balance by RCA's "police." But the more shrews manufacturers began to work through the courts, attacking RCA's hold on the patents. The Armstrong patents began to weaken, as claim after claim was stricken as following "prior art." The fact that the telephone company had operated successful superhets as early as 1919 in their phone systems and in broadcast stations, based on Levy work in France in WWI, hurt the RCA case tremendously and was often used by radio manufacturers in battling RCA in court. To prevent further attack on the basic patents, and to reduce the perception that the RCA monopoly was harmful, Sarnoff retracted his earlier statement that the superhet would belong to RCA alone. He began to issue licenses for the circuit, and the "little guys" lined up to sign up.

The development of the tetrodes, pentodes, and then pentagrid tubes really solved the economics problem for the superhet. We all know the All-American Five story, the "standard" five-tube superhet radio, operated directly from a.c. or d.c. line, and selling anywhere from $7.95 to $100. It marked the acme of the superhet's broadcast band popularity. Despite the Depression of 1930 - 1939, this set continued to hold companies together, as nearly every home eventually wound up with one, two, or even three such sets plus a console, which was also a superhet.

But in the short-wave bands, the superhet found serious tuning-drift problems. In the home, where casual listening to international broadcasts was the only use of short-wave, drift simply meant that the listener had to tweak the tuning dial a tad as the set was warming up, to keep the desired station on channel. Several automatic frequency control schemes were used from time to time in the '30s, especially in "quick tuned" sets like Grunow's Teledial. These were good in the broadcast band where there was freedom from severe fading, but in the short-wave bands the fading problems, caused by the basic radio wave propagation problems, made these electronic tuning methods troublesome. For the serious radio listener (military, amateur, or professional short-wave monitor), the answer to frequency drift was to design expensive, mechanically stable tuning circuits. The basic problem is that at short-wave frequencies, say 10 megahertz, a drift in the superhet's local oscillator of only one-hundredth of one percent is equivalent to shifting the desired signal by 1000 cycles per second (cps, or Hertz). For a Morse signal set to, say, 400 Hz keying tones, the tones would have shifted to 1400 Hz, or over 200 percent. This is a result of the heterodyning process which shifts the incoming 10-MHz signal all the way down to the 400 Hz tone by subtracting the incoming signal frequency from that of the drifting oscillator.

But stable mechanical designs, calling for massive, precision-made tuning capacitors, were not the ultimate answer. For working a few radio channels, designers had long been using quartz crystal control of local oscillators, but when many frequencies had to be tuned in, the number of crystals became onerous and, except for the military, such radios had limited popularity. So firms like Cardwell, James Millen, National, Hammarlund, and General Radio became the standard suppliers to the enthusiast trade for tuning capacitors of precision, and crystal-controlled reception was resorted to for organized, netted communication links used by hams and the military.

But Collins Radio had a better idea, and it was the beginning of a new revolution in the superhet circuit.

The inevitability of America's entry into World War II impelled the military services to a transition, in 1940, from a peacetime attitude to one of some urgency. The communications equipment used by the two major services plus the Army Air Corps included much of the same gear as was in use in 1932. It is true that newer radio equipment was in the inventory, but in small quantities, so that the communication links of the day had to work to the capacities of the poorest equipment suite in the network, sort of the "weakest link" principle. The superheterodyne receiver was there, in many forms, and representing many generations in the evolution of that circuit. A look at the tube complements alone serves to illustrate this point. Navy airborne sets used tubes like 6C6, 6D6, 78, 77, and 75 in some instances, and modern octal metal tubes in others. Some Army field sets still used 30s, 31s, and UX199s, while others were just coming off the drawing boards with 1T4s,1L4s, 3Q5s, and other miniature tubes. Transmitters were far more interchangeable because nothing revolutionary had happened in the transmitter field for about ten years. But a single common factor in all military communications was that ever higher frequencies were being used for tactical communications, while the good old short-wave bands were still in use for long-haul circuits.

This use of higher frequencies emphasized the frequency drift problem in superhets. Even the use of very massive, precision-built variable capacitors didn't keep the local oscillators from drifting seriously. Resort to crystal control mean a loss in flexibility, and a potential breakdown in netting several military units because of the inability to scan (in search of the right frequency) the crystal-controlled sets. The Collins Radio Company sought to cure this problem by cascading two radio receivers, both of them superheterodynes. The first used a crystal-controlled local oscillator in which a number of crystals, cut at uniformly spaced frequencies served to heterodyne the incoming signals to a broadly tuned intermediate frequency. This i.f. signal was then passed to the second receiver where it was fine-searched for the desired signal. Hams had been doing this same thing for several years, calling the second receiver a "Q-5er." But Collins' first heterodyne soon became set to integer megahertz at the radio input, such that the second receiver became an interpolating instrument to read frequencies between the integer megahertz. Then Collins converted the first local oscillator to a single crystal-controlled type, whose output was deliberately distorted. This made it rich in harmonics of the crystal frequency. Thus if the crystal were cut for exactly one MHz, the oscillator output contained signal components at 1, 2, 3, 4, 5, etc., MHz. To select which harmonic to use for any given listening frequency interval, the selection knob not only tuned the receiver input circuit to the desired listening frequency regime, but it was ganged to a tuned circuit which selected the proper oscillator harmonic. Now ma single crystal, cut for a standardized frequency (1,000 MHz, for example), was all that the receiver needed.

For still higher frequencies, this process was repeated, with the first heterodyne local oscillator set at 10 MHz intervals, the second heterodyne set at 1 MHz intervals, and then the signal entered the conventional superhet interpolation receiver section. At the conclusion of the war, the few such experimental sets Collins had completed put the company in the vanguard of new superhet design, and the famous R-390 was the finished product. Collins built thousands of these sets for the services, until other manufacturers finally were able to beat Collins' manufacturing costs, and the final production runs were in Motorola's and several other shops. The R-390 is a mechanical marvel, not because Collins had to build precision and stability into the variable capacitor, but because of the number of tuned circuits needed to preselect the input frequency range, to select the proper local oscillator harmonics (for several local oscillators), and finally to tune the fine-tuning receiver section. What complicated the matter was the problem many engineers had found in all-wave sets, namely the production of tuning "birdies." These are little (and sometimes BIG) squeals and tweets produced unintentionally, but inevitably, as a result of various harmonics of the input signals, or of the local oscillator signals, or both, heterodyning with each other in each frequency-changing stage. In the Collins design, which used triple conversion (three heterodynes cascaded), the opportunity for birdie production was rich.

For this reason, the R-390 heterodynes the input signal upward, not downward, as Armstrong needed to do it, to a very high frequency. This process, called VHF up-conversion, has become standard in all quality all-wave sets made since the Korean War.

But a South African named Wadley finally eliminated the mechanical complexity of Collins design. His circuit also up-converted the input signal, and with a rather routine local oscillator of modest drift capabilities. It ranged in frequency from 40.5 MHz to 69.5 MHz, for input signals from near zero frequency to 30 MHz, in one-MHz intervals. But this same local oscillator also heterodyned with the harmonic-rich output of the Collins-type standardized crystal oscillator, producing an auxiliary, steady heterodyne output only when the auxiliary signal was at 37.5 MHz, owing to its having to pass through a sharply tuned 37.5 MHz circuit.

Thus the first local oscillator, which might tend to drift, has to be set to any frequency ending with a half-megahertz in order to produce an output from the 37.5 MHz auxiliary heterodyne output. And it has to be set approximately to the integer-plus-a-half MHz, because the 37.5 MHz sharply tuned circuit isn't infinitely sharp, after all. Now this 37.5 MHz tone is used as a local oscillator signal to heterodyne with the first i.f., namely that product of the input signal and the first local oscillator. The output of this last conversion stage is a 2 MHz to 3 Mhz band of signals, which is passed finally to a Collins-type conventional fine-tuning receiver section. The Wadley loop, as this circuit is called, has the beautiful feature that the drifty first local oscillator has its drift canceled by being injected twice, once to add frequency to the input, and once to subtract

The receiver that first utilized the Wadley loop principle was the British Racal RA-17, classed among the very finest receivers of its day. Although Wadley developed the basic circuit in 1940, the RA-17 didn't become commercially available until the 1950s, the British military being the only beneficiary of the Wadley loop in the intervening period. The RA-17 is still one of the rare prizes at hamfests, often commanding prices of $400 or more.

Of course, today's all-wave superhets use very modern frequency synthesizers to create highly stable local oscillator signals, such that drift is nearly unheard of. The price paid for this drift-free quality is a reduced quality everywhere else. In dynamic range (the ability to handle, simultaneously, large and small signals), they are miserable, compared to the old tube-type sets of the 30s and 40s, and birdies still abound. And, of course, there is no sound quality like that found in the good old days, in the Scotts, the Zeniths, and the Philcos.

From the controversial beginnings of the superheterodyne, which everyone will admit was first made popular and practical for the consumer by Edwin Armstrong, we have seen primitive catacomb circuits full of birdies transformed through the years to very high quality conventional sets like the Scott All-Waves, finally to Collins and Wadley loop sets marking the end of tube-types, and to the fully synthesized, microprocessor-controlled gems from Japan, and we're back to birdies and tinny sound. But we have hope. There are a few superb sets out there today, for the enthusiast, just as there were in Leutz's day. And there are always the Over-the-Horizon Radar systems, which use all-wave superhet receivers of phenomenal quality. And at a hundred thousand bucks a piece, they should be good.

THE SUPERREGENERATIVE CIRCUIT

SOME RECENT DEVELOPMENTS OF REGENERATIVE RECEIVERS...Edwin H. Armstrong,
Proc. of the Institute of Radio Engineers,
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SOME RECENT DEVELOPMENTS OF REGENERATIVE RECEIVERS

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It is the purpose of this paper to describe a method of amplification which is based fundamentally on regeneration, but which involves the application of a principle and the attainment of a result which it is believed is new. This new result is obtained by the extension of regeneration into a field which lies beyond that hitherto considered its theoretical limit, and the process of amplification is therefore termed *super-regeneration.*

Before proceeding with a description of this method it is inorder to consider a few fundamental facts about regenerative circuits. It is well known that the effect of regeneration (that is, the supplying of energy to a circuit to reinforce the oscillations existing therein) is equivalent to introducing a negative resistance reaction in the circuit, which neutralizes positive resistance reaction, and thereby reduces the effective resistance of the circuit. There are three conceivable relations between the negative and positive resistances: namely -- the negative resistance introduced may be less than the positive resistance, it may be equal to the positive resistance, or it may be greater than the positive resistance of the circuit.

We will consider what occurs in a regenerative circuit containing inductance and capacity when an alternating electromotive force of the resonant frequency is suddenly impressed for each of the three cases. In the first case when negative resistance is less than the positive), the free and forced oscillations have a maximum amplitude equal to the impressed electromotive force over the effective resistance, and the free oscillation has a damping determined by this effective resistance. The steady state is attained after the initial free oscillation dies out and continues until the impressed emf. is removed, when the current dies out in accordance with a second free oscillation.

The maximum amplitude of current in this case is always infinite; it reaches this maximum amplitude in a finite time, and when the impressed emf. is removed the current dies away to zero.

This is the action of the circuits which are now in every-day practical use. In the second case the negative resistance is equal to the positive resistance, and the resultant effective resistance of the circuit is therefore zero. When an emf. is suddenly impressed in this case, the current in the circuit starts to increase at a rate which is directly proportional to the impressed electromotive force and to the square root of the ratio of the capacity to the inductance of the circuit (for a given impressed frequency).

If the force is impressed for an infinite time, then the current in the circuit reaches infinity. If the emf. is impressed for a finite time, then the current reaches some finite value. When the impressed emf. is removed, the current in the circuit at that instant continues indefinitely with unchanged amplitude as a free oscillation. Theoretically, this is the limiting case for regeneration; practically, it is always necessary to operate at some point slightly below this state at which the circuits have a definite resistance.

It is important to note here that altho the circuit of this case has zero resistance, oscillations will not start unless an emf. is impressed upon the circuit; furthermore, that oscillations once started continue with undiminished amplitude indefinitely. This state cannot be attained in practice, because the negative resistance furnished by the tube is dependent on the amplitude of the current and for stable operation decreases with increasing amplitude.[1]

In the third case the negative resistance introduced into the circuit is greater than the positive resistance, and the effective resistance of the circuit is therefore negative. When an emf. is impressed upon a circuit in this condition, a free and a forced oscillation are set up which have some interesting properties. The amplitude of the forced oscillation is determined by the value of the impressed emf. divided by the resultant resistance of the circuit. The free oscillation starts with an amplitude equal to the forced oscillation, and builds up to infinity regardless of whether or not the external emf. is removed. This free oscillation starts with an amplitude which is proportional to the impressed force, and this proportionality is maintained thruout any finite time interval (with constant impressed electromotive force).

It is important to note that altho the negative resistance of the circuit exceeds the positive, and the effective resistance of the circuit is negative, oscillations will not occur until some emf. is impressed. *Once an emf. is impressed, however, no matter how small it may be, the current in the circuit builds up to infinity regardless of whether or not the external emf. is removed.*

The fundamental difference between the case in which the resistance of the circuit is positive and the case in which the resistance of the circuit is negative may be summed up as follows: in the first, the forced oscillation contains the greatest amount of energy and the free oscillation is of very minor importance[2] (after a short interval of time), in the second, it is the free oscillation which contains the greatest amount of energy and the forced oscillation which is of negligible importance.

It is, of course, impossible with present-day instrumentalities to set up a system in which the negative resistance exceeds the positive without the production of oscillations in the system, since any irregularities in filament emission or impulse produced by atmospheric disturbances is sufficient to initiate an oscillation which builds up to the carrying capacity of the tube. It is, however,possible, by means of various expedients, to set up systems which avoid the production of such a paralyzing oscillation and which approximates the theoretical case in the use of a free oscillation to produce amplification.

The first use of the free oscillation in a regenerative system for the amplification of signals appears to have been made by Turner[3] in his valve relay system. Briefly, Turner prevented the regenerative circuit from producing oscillations when no signals were being received by placing a negative potential on the grid of sufficient value to hold it just below that point on the characteristic curve at which self-oscillation would start. The impressing of a small electromotive force of sufficient value would carry the potential of the grid over the "threshold" value and a free oscillation would start which would build up to the limiting value of the tube.

The system was returned to its initial sensitive state by means of a relay operated by the increase in the plate current of the tube. This relay short-circuited the feed-back coil, thereby cutting off the supply of energy and permitting the potential of the grid to drop back below the "threshold" value. As Turner explains, the device is a relay with a low limit (as distinguished from an amplifier), but it appears to be the first device in which free oscillation set up by an impressed electromotive force produced the magnified result.

Bolitho[4] contributed an important improvement by replacing the mechanical relay of Turner which operat- ed only upon the receipt of a signal by a valve relay which was continuously operated by independent means. Briefly, this was accomplished by connecting a second valve to the oscillating circuit of the Turner arrangement with a reverse feed-back connection and supplying the plate circuit with alternating current.

When the "threshold" value of the first tube was overcome and a free oscillation started in the system, the reversed feed-back of the second tube comes into action and at that time when the voltage supplied to the plate is positive,damps out the free oscillation and permits the grid of the first tube to return below the "threshold" value. This represents the second step in the utilization of the free oscillation for the production of amplification.

It is the purpose of this paper to describe a principle of operation based on the free oscillation which is quantitative and without a lower limit. This new method is based on the discovery that if a periodic variation be introduced in the relation between the negative and positive resistance of a circuit containing inductance and capacity, in such manner that the negative resistance is alternately greater and less than the positive resistance, but that the average value of resistance is positive, then the circuit will not of itself produce oscillations, but during those intervals when the negative resistance is greater than the positive will produce great amplification of an impressed emf.

The free oscillations which are set up during the periods of negative resistance are directly proportional in amplitude to the amplitude of the impressed emf. The variation in the relation between the negative and positive resistance may be carried out by varying the negative resistance with respect to the positive, by varying the positive resistance with respect to the neg- ative, or by varying both simultaneously at some frequency which is generally relatively low compared to the frequency of the current to be amplified.

These three methods of producing super-regenerative state are illustrated respectively in Figures 1, 2, and 3, which figures indicate the general scheme of the system and the methods of varying the relation between the negative and positive resistance. Figure 1 shows a method of varying the negative resistance produced by the regenerative system by varying the voltage of the plate of the amplifying tube by means of a second tube, the grid of the second tube being excited by an emf. of suitable frequency.

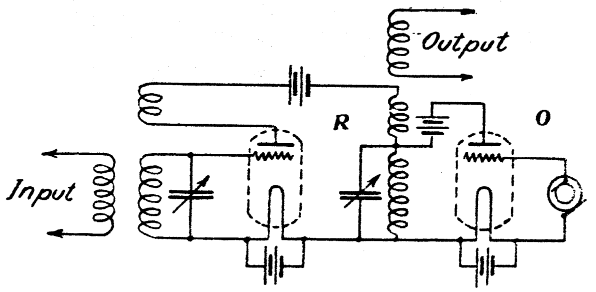

FIGURE 1

Figure 2 illustrates a method of varying the positive resistance of the circuit with respect to the negative. This is accomplished by connecting the plate circuit of a vacuum tube in parallel to the tuned circuit of the regenerative system and exciting the grid by an emf. of suitable frequency.

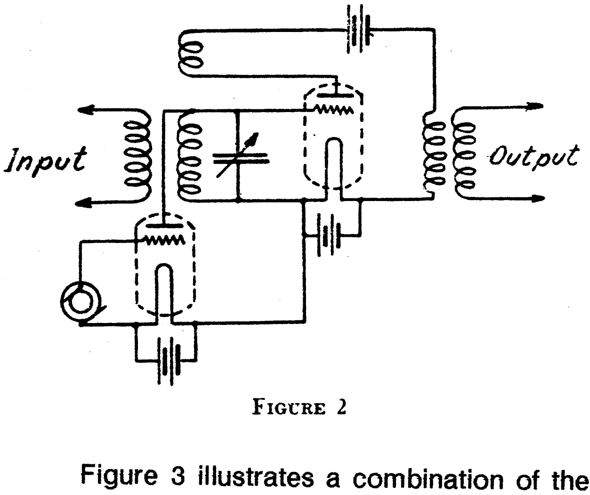

FIGURE 2

Figure 3 illustrates a combination of these two systems in which simultaneous variations are produced in both the negative and positive resistances and provisions made for adjusting the relative phases of these two variations.

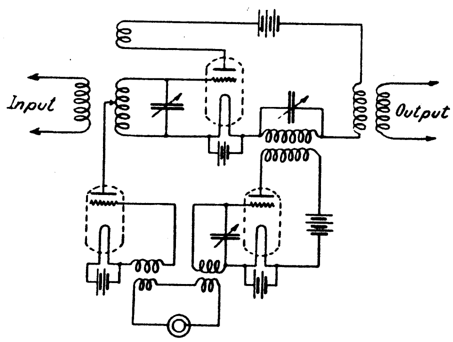

FIGURE 3

A general idea of the phenomena occurring in these systems when an emf. is applied to the input circuit will be obtained from the diagram of Figure 4 which applies specifically to the circuit of Figure 1.

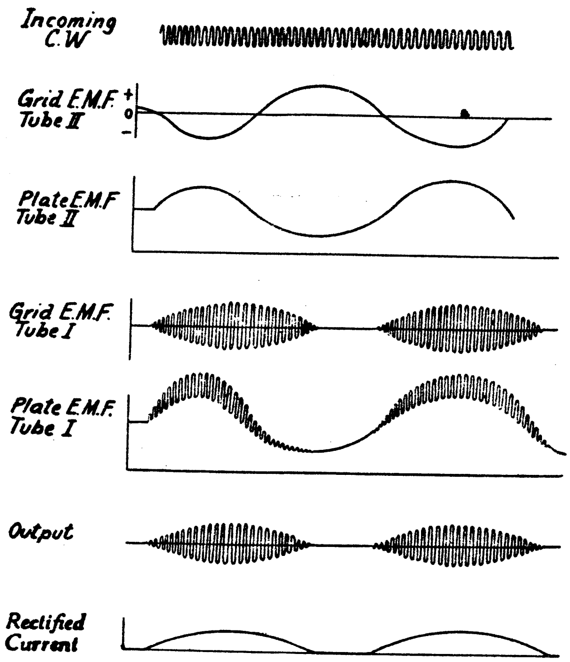

FIGURE 4
Tube I refers to R in Figure 1
Tube II refers to O in Figure 1

This figure illustrates the principle relations existing in the system in which the positive resistance is constant and the variation is introduced into the negative resistance. It will be observed that the frequency of variation appears as a modulation of the amplified current so that the output circuit contains currents of the impressed frequency plus two side frequencies differing from the fundamental by the frequency of the variation.

Oscillograms of the essential current and voltage relations existing in the systems of the type illustrated by Figures 1 and 2 were obtained with the set up of apparatus illustrated in Figures 5 and 6 respectively.

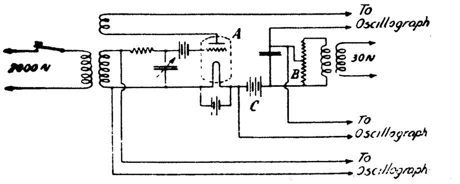

FIGURE 5
A-4 Western Electric Type L Tubes in parallel
B-AC Voltage = 100 Volts
C-DC Voltage = 160 Volts

In the arrangement of Figure 6, in order to produce sufficient variation in the positive resistance of the tuned circuit, which was of large capacity and low inductance, it was necessary to use a two-electrode tube in series with the auxiliary emf.

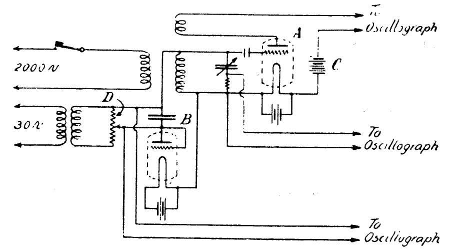

FIGURE 6
A-4 Western Electric Type L Tubes in parallel
B-1 Western Electric Type L Tubes with grid and plate in parallel
C-DC Voltage = 160 Volts
D-AC Voltage = 30 Volts

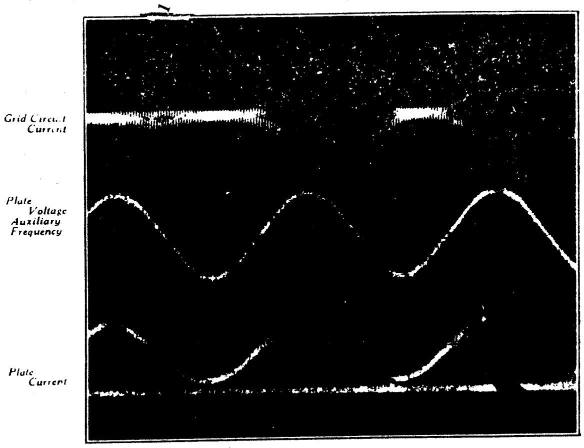

FIGURE 7

Figures 7 and 8 are oscillograms respectively for a negative resistance variation and a positive resistance variation. The signaling emf. was impressed about half way along the film, the exact point at which the key was closed being indicated by the arrow. These oscillograms show phenomena which are in accordance with the explanation already given, but, in addition,show evidence of self excitation.

It has been stated in the preceding pages of this paper that the basis of super-regeneration was the discovery that a variation in the relation between the negative and positive resistances prevented a system which would normally oscillate violently from becoming self-exciting. An examination of the oscillograms will show that this is not strictly true, as a free oscillation starts every time the resistance of the circuit becomes negative. It will be observed however, that this free oscillation is small compared to that produced by the signal, and therein lies the complete explanation of the operation of the system.

The free oscillations produced in the system when no signaling emf. is impressed, must be initiated by some irregularity of operation of the vacuum tubes, and must start at an amplitude equal to the amplitude of this disturbance. This initial value is of infinitesimal order, and hence, in the limited time interval in which it can build up the locally excited oscillation, never reach an amplitude comparable to the oscillation set up by a signal of any ordinary working strength.

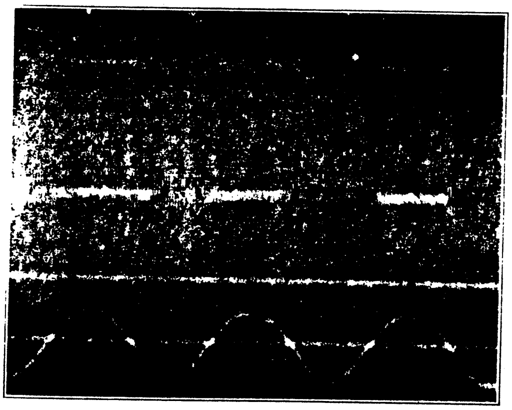

Figure 8

There is a second point of interest which is most evident from the curves of Figure 7. It will be observed that there is a decided lag in the maximum value attained by the free oscillation set up by a signal and the maximum value of plate voltage (negative resistance) of the amplifying tube. This is most evident from the plate current curve. It is a point of considerable interest, and the phenomena involved will be analyzed in a later part of the paper.

The rate of variation in the relation between the negative and positive resistance is a matter of great importance. It may be at sub-audible, audible, or super-audible frequencies. In radio signaling, for the reception of telephony, the variation should be at a super-audible frequency. For modulated continuous wave telegraphy and spark telegraphy, to retain the tone characteristics of the signal, it must be well above audibility; for maximum amplification a lower and audible rate of variation should be used. In continuous wave telegraphy, where an audible tone is required, the variation is at an audible rate; where the operation of an indicating device is required, a sub-audible frequency may be best. The choice of frequency is a compromise, particularly in telephony, since obviously the lower the frequency the greater the amplification, and the higher the frequency the better the quality.

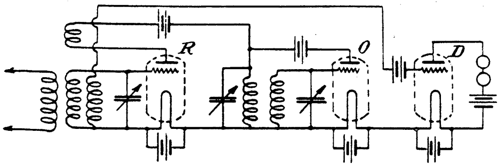

Figure 9

Some practical forms of circuits are illustrated by Figures 9, 10, and 11, which illustrate respectively the three types of variation. Figure 9 shows a method of varying the plate voltage of the amplifying tube *R* by means of the vacuum tube oscillator *O* coupled into the plate circuit. In this arrangement a third tube *D* acts as a detector. This is essential when an audible frequency is employed; when a super-audible frequency is used the telephones can be placed directly in the plate circuit of the amplifying tube.

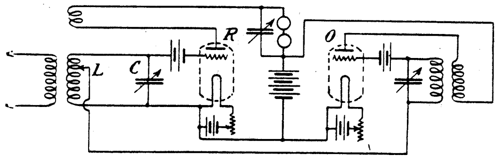

Figure 10

Figure 10 shows the second case in which the variation is introduced into the positive resistance of the tuned circuit. This is done by means of an oscillating tube *O*, the grid circuit of which is connected thru the tuned circuit *LC* of the amplifying tube *R*. The variation in the resistance of the circuit is effected thru the variation in potential of the grid of the oscillating tube. During that half of the cycle, when the grid of the oscillating tube is positive, energy is withdrawn from the tuned circuit in the form of a conduction current from the grid to the filament of the oscillating tube, thereby increasing the effective resistance of the circuit. During the other half of the cycle, when the grid of the oscillating tube is negative, no conduction current can flow thru the grid of the oscillating tube, and hence no resistance is introduced into the tuned circuit of the amplifying tube.

In this case the amplifying tube serves also as the detector for any frequency of variation, as the tuned circuit forms a sufficiently good filter even for an audible frequency to prevent a disturbing audible tone in the telephones.

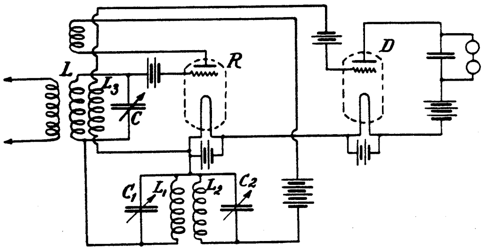

FIGURE 11

Figure 11 illustrates the case of a simultaneous variation in both positive and negative resistances. This is accomplished by providing the amplifying tube R with a second feed-back circuit L_1C_1 and L_2C_2 adjusted to oscillate at some lower frequency, thereby introducing a variation in the negative resistance thru the variation of the plate potential of the amplifier and a variation in the positive resistance by means of the variation of the grid of the amplifier. The proper phase relations between negative and positive resistance are obtained by adjustment of the capacity of condensers C_1 and C_2 and the coupling between L_1 and L_2. In operation this system is very critical, and extreme care is necessary in order to obtain the super-regenerative state.

In each of the preceding cases the detecting function has been carried out either by a separate tube or by means of the amplifying tube. When a super-audible frequency of variation is employed, it is sometimes of advantage to perform the detecting function in the oscillating tube, and an arrangement for carrying this out is illustrated in figure 12.

The operation of the system is as follows: incoming signals are amplified by means of the regenerative action of the amplifier tube R and the variations of potential across the tuned wave frequency circuit LC impressed upon the grid of the oscillating tube O. These oscillations are then rectified, and two frequencies are produced in the circuits of the amplifier tube. One of these frequencies corresponds to the frequency of modulation of the signaling wave.

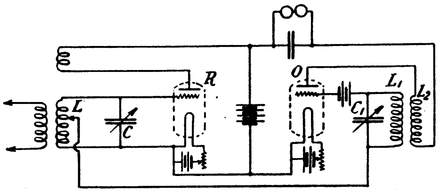

FIGURE 12

The other corresponds to the frequency of the variation and contains a modulation in the amplitude corresponding to the modulation of the transmitted wave. The second frequency is then impressed upon the circuits of the oscillating tube with which it is in tune, amplified by the regenerative action of the system $L_1C_1L_2O$, and then rectified. The amplification obtainable with this form of system is considerably greater than that of the single amplification circuits, but is naturally more complicated to operate.

When a super-audible variation is employed in a system such as illustrated in Figure 1, it is generally necessary to introduce a certain amount of resistance in the tuned circuit to insure the dying out of the free oscillation during the interval when the resistance of the circuit is positive.

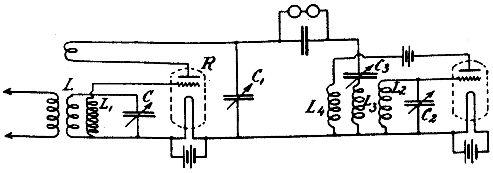

FIGURE 13

This is most effectively carried out by means of the arrangement illustrated in Figure 13, in which a secondary coil L_1 of large inductance and high resistance is coupled to the tuned circuit LC and the energy withdrawn thereby from the oscillating circuit stepped up and applied to the grid of the tube. In the operation of this system, a curious phenomena is encountered. This is the manifestation of an inductive reaction by the plate circuit of the amplifying tube to the auxiliary frequency emf. supplied the plate circuit by the oscillating tube, which comes about in the following way.

When the auxiliary emf. is impressed upon the plate of the amplifying tube, a current is produced in this tube in phase with the emf. across the tube. Now suppose the plate voltage is at its maximum positive value. This means that the negative resistance of the circuit is a maximum in amplitude. This in turn means that the average value of the grid is becoming more positive and the current in the plate circuit is likewise increasing.

Since the free oscillation in the system will increase in amplitude as long as the resistance of the circuit is negative, it will reach its maximum amplitude after the maximum positive voltage is applied to the plate. Hence the component of current corresponding to the frequency of the variation set up in the plate circuit by the rectification of the radio frequency oscillations lags in phase behind the auxiliary emf. impressed on the plate. Hence the plate circuit of the tube manifests an inductive reaction to the auxiliary emf.

It was found that this inductive reaction could be tuned out by means of the parallel condenser C_1 with a great improvement in the stability of the operation of the system and increase in signal strength. The resonance point is pronounced, and once the other adjustments of the system have been correctly made is as readily found as any ordinary tuning adjustment.

The problem of cascade amplification with these systems is a rather involved one on account of a great number of effects which are not encountered in ordinary methods of cascade amplification. The principal trouble is the reaction of the second amplifying system on the first, and the difficulty of preventing it in any simple way on account of the high amplification per stage. While this difficulty is not insuperable, a simple expedient may be employed which avoids it. On account of the large values of radio frequency energy in these amplifying systems, the second harmonic is very strong in the plate circuit of the amplifying tube and is of the same order of magnitude as the fundamental if the tube is operated with a large negative voltage on the grid.

Hence by arranging the second stage of a cascade system to operate at double the frequency and to amplify this harmonic, the difficulty is avoided. The general arrangement of such a system is illustrated by Figure 14, in which the positive resistance of the circuits LC and L_1C_1 of a two-stage amplifier are varied synchronously by a single oscillator. The circuit L_1C_1 in this case is tuned to the second harmonic of the circuit LC, but the combinations of circuits which may be arranged on this principle are very numerous.

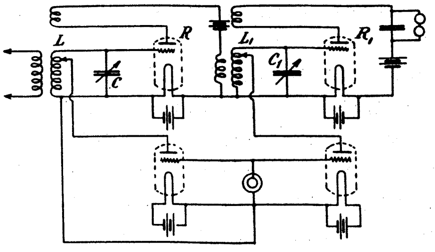

FIGURE 14

One of the curious phenomena encountered with the super-regenerative system is found when it is attempted to secure sharp tuning by the use of tuned circuits placed between the antenna and the amplifying system. The free oscillations set up in these circuits by the reaction of the amplifying system continue in these circuits during the interval when the resistance of the amplifier circuit is positive, re-excite the amplifier when the resistance becomes negative, and hence the entire system is kept in a continuous state of oscillation.

The effect is most critical, and may be produced with most extremely weak couplings between the amplifier circuit and the second tuned circuit. The simplest solution of the difficulty is to perform the function of tuning at one frequency and amplification at another, and this is best accomplished by means of the super-heterodyne method illustrated in Figure 15.

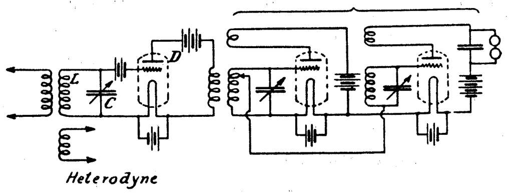

FIGURE 15

This may be adapted to work on either the sum or difference frequencies, but when the higher frequency is used, care should be taken that it is not near the second harmonic of the local heterodyning current. In the particular arrangement illustrated, *LCD* represents, together with the heterodyne, the usual agency for changing the incoming frequency, and *A* represents the super-regenerative amplifier which may be of any suitable type.

Some of the results obtained in practice with super-regenerative systems compared to simple regenerative systems may perhaps be of interest. In general, it may be stated that the amplification which can be obtained varies with the frequency of the incoming signal and with the ratio of the wave frequency to the auxiliary frequency. The higher the signaling frequency and the greater the ratio of this frequency to the auxiliary frequency, the greater the amplification. Other things being equal, it appears that the energy amplification varies as the square of the ratio of the signaling frequency to the auxiliary frequency. Hence, it follows that for telegraphic signals where an audible auxiliary frequency is used, much greater amplification can be obtained than in the case of telephone, where a super-audible auxiliary frequency must be employed.

Using the arrangement of Figure 11 for a signaling frequency of 500,000 cycles, an energy amplification of several million times greater than that obtainable with a simple self-heterodyne circuit is readily secured. Where a super-audible frequency is used for the reception of telephone signals, amplification of 50,000 to 100,000 times energy can be obtained.

In a practical way the relative amplification of the new system with respect to the standard regenerative system for reception of telephone signals may be visualized as follows: With a signal so extremely weak that only the faintest of beat notes can be heard in the ordinary regenerative receiver, the super-regenerative receiver will give clearly understandable speech. For signals of sufficient strength to be understandable with the ordinary regenerative system with zero beat adjustment but not audible without local oscillations, the super-regenerative receiver will produce signals loud enough to be heard thruout the room.

Perhaps the most surprising characteristic of the system, apart from the amplification, is its selectivity with respect to spark interference when a super-audible frequency of variation is used. The explanation of this selectivity with respect, for example, to the ordinary regenerative receiver, lies in the periodic suppression of all free vibrations in the system. In the ordinary regenerative system spark interference approximates a form of shock excitation setting up a free vibration in the system which, because of the low damping existing therein, continues for a long period of time.

An examination of the character of the oscillation set up will show that the energy existing in the free vibration after the initial impressed electromotive force is removed, is far greater than the forced vibration. In the ordinary system this free vibration may exist for a thousandth of a second or more. In the super-regenerative system this free vibration is damped out before it has proceeded more than one twenty-thousandth of a second as a maximum. Hence, the interference from spark signals is greatly reduced. This phenomenon opens up a new field for the suppression of interference produced by shock excitation.

At the present time, on a three-foot loop antenna located 25 miles from station WJZ at Newark, New Jersey, and a system of the type illustrated in Figure 12 with one stage of audio frequency amplification (three tubes in all) the announcements and musical selections are clearly audible five hundred yards from the receiver. With the same loop at the same distance, using the arrangement of Figure 11 without the separate detector tube, that is, with the telephones directly in the plate circuit of the amplifier tube, it is possible to operate a loudspeaking telephone so that the program is plainly heard thru a large size room.

The signals with arrangements of either Figure 11 or 12 are still heard loudly if the loop is discontinued from the receiver, the coils and wires of the receiver itself collecting sufficient energy to produce response.

While the new system does not amplify the ordinary spark signal with anything approaching its efficiency on continuous wave signals, one example of spark reception may be of interest. During the past Winter an amateur spark station located at Cleveland, Ohio, and operating on a wave length of about 340 meters was received nightly at Yonkers, New York, on a three-foot (1 meter) loop and the arrangement of Figure 13 with sufficient intensity to enable the signals to be read thruout the room.

In conclusion, I wish to express my very great indebtedness to Professor L. A. Hazeltine for much valuable aid in connection with the theoretical side and to Mr. W. T. Russell for his assistance thruout the experimental side of this development.

SUMMARY

A system of circuits is described whereby the effective resistance of a regenerative circuit is periodically made positive and negative, tho' predom- inantly positive. Such a circuit will respond to impressed electromotive forces by setting up free oscillations during the negative resistance period, which oscillations are proportional to the exciting emf. The forced oscillations produced by the exciting emf. will be comparatively small. The free oscillations caused by any normal variations in tube operation will also be small.

Means of carrying out regenerative circuits thru the requisite resistance cycles are shown, and the practical operation of the system, including the case when extreme amplifications are desired, is discussed.

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[1] It is very important at this point to distinguish between the purely theoretical state and the state which exists in oscillating tube circuits. In the various forms of self-heterodyne circuits a free oscillation of constant amplitude is maintained in the system and the circuit may be considered as having zero resistance, *but only for that particular amplitude of current.* An external emf. impressed on the circuit always encounters a positive resultant resistance, assuming, of course, that the existing oscillation is stable. This is due to the non-linear characteristics of the tube.

[2] This is strictly true when dealing with continuous waves which we have been considering. It is not true in the regenerative reception of spark signals, particularly of short wave length, large damping, and low spark frequency. In this case the energy in the free oscillation exceeds the energy in the forced oscillation.

[3] British Patent, 130,408.

FREQUENCY MODULATION

EDWIN HOWARD ARMSTRONG AND THE HISTORY OF FM RADIO...David Morton

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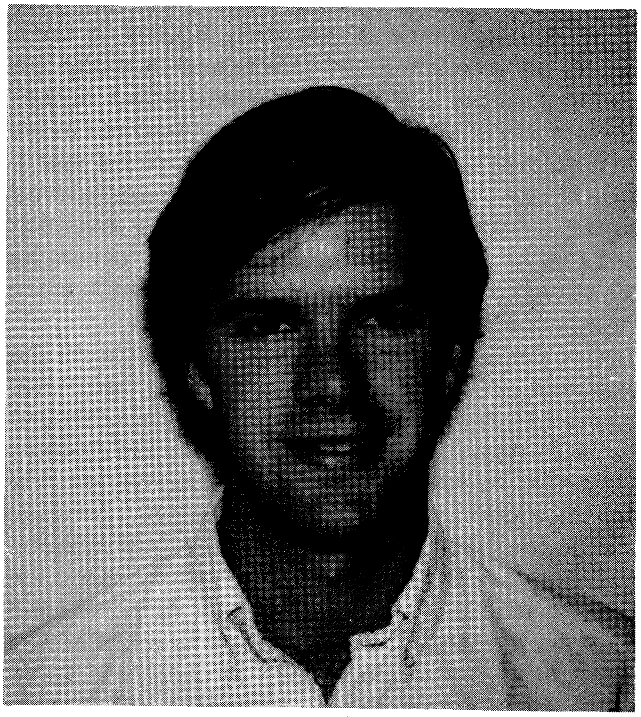
EDWIN HOWARD ARMSTRONG AND THE HISTORY OF FM RADIO:
A CONTEXTUAL APPROACH

by **David L. Morton, Jr.**

Those historians who have concerned themselves with the history of electronics have done little to document the history of radio and broadcasting occurring in the period after about the 1920s. Huge gaps in the record also appear when one searches for the story of audio electronics industry of the post-World War II era. It is of course not until after the second World War that the evolution of the consumer radio and phonograph technologies began to accelerate, and to do so at breakneck speed. Even as a confusing array of new electronic entertainment devices become ubiquitous in our lives now, we may search for but will not find the history of consumer entertainment electronics in the critical post-war period when the combination of trends in electronic technology and American society were reaching "critical mass."

One of the most important of these post-war technologies is commercial FM radio, and the man credited with the invention of the FM system used commercially in the United States is Edwin H. Armstrong. Armstrong appears in literature most notably as the subject of two books, both of which seek, in a didactic sort of way, to paint a picture of Armstrong as simply a heroic inventor pitted against the evil forces of The Corporation.[1] Without denying that much of what these books say is entirely on the mark, even a cursory examination of the literature written by or about Armstrong suggests that an analysis which would place Armstrong into the larger context of American history would provide us with a better way to judge his historical significance, or to explain fuller the "real" hows and whys of his career. The emergence of FM is not simply the result of Armstrong's heroic battle with the FCC or RCA, but it is also part of a larger current of historical events.

This essay argues that the early history of FM was in fact shaped by Armstrong's distinctive personal characteristics: his dogged interest in the disposition of federal regulation and of patent litigation, and his particular "style" of invention. But the second World War marked a turning point in FM history after which the flow of history of FM widened and overtook Armstrong. Thereafter, Armstrong's personal role was much less important in FM's development. In this essay, I have surveyed the published literature relevant to Armstrong's career and his FM system, and have analyzed some of the more significant facets.



David L. Morton, Jr.

The history of frequency-modulated radio broadcasting dates from the second decade of the twentieth century, but a commercially-viable system did not appear until Armstrong revealed his in the early 1930s. The primary difference between the early proposed FM systems and the commercial broadcast system universally adopted by the early 1920s was, of course, the mode of modulation. Radio transmits information by converting sound waves into analogous electromagnetic waves that are broadcast into the atmosphere. A radio receiver detects the waves and uses electrical circuits to convert the signal back into sound. An FM system broadcasts a signal which varies its frequency in a pattern analogous to the original sound. An amplitude modulated system, on the other hand, transmits an electromagnetic signal of varying intensity. For a variety of reasons, AM came to be the standard method of commercial broadcasting in the United States during the early 1920s. FM, however, remained in the laboratory.[2]

Edwin Howard Armstrong, born in New York in 1890, like many of the early figures in radio history became interested in "wireless" as a boy. He graduated from Columbia University with a degree in electrical engineering, in 1913. He served in the Army Signal Corps in Europe during World War I, where he conceived his highly-acclaimed superheterodyne radio circuit. His major invention before FM, including the regenerative circuit he discovered as an undergraduate, all were improvements to AM radio technology.[3]

Armstrong's inventions were crucial to the explosive growth of commercial radio in the 1920s, and during this period radio technology appeared to be reaching a mature state. Interest in FM systems remained, however, and over the years various FM schemes were attempted experimentally. Through the early 1930s, while AM technology became entrenched in the United States, no new broadcasting system emerged that could exceed AM's performance. Yet engineers recognized the many flaws of AM and hoped to overcome them. AM suffered from being susceptible to interference from a variety of natural and man-made sources, and frequently AM broadcasts were quite "noisy." Engineers who tested experimental FM systems as an alternative, however, found that the disadvantages of FM outweighed any of the possible benefits.

A widely-read paper published in the *Proceedings of the IRE* in early 1922 demonstrated mathematically the advantages of AM broadcasting over all known FM systems. The author, John R. Carson, was mathematically employed in the research and development division of American Telegraph & Telephone. His article was an attack upon the proposal to use FM transmission as a way to narrow the band of frequencies required for a radio broadcast, which in turn would conserve space on the increasingly-crowded radio dial. Carson demonstrated mathematically, however, that FM broadcasting requires a bandwidth at least twice as great as the highest modulating frequency, and thus the bandwidth is equal to or wider than that required for a comparable AM broadcast. This finding seemed to negate one of the most important potential advantages of FM transmission.[4]

Carson also attempted to demonstrate mathematically how electrical disturbances affected AM and FM broadcasts. One of the most fundamental problems with commercial AM broadcasts was atmospheric disturbances and interference from competing stations. Again, the conventional wisdom taught that a narrower band of frequencies utilized for broadcasting would allow less atmospheric disturbance into the signal. In quantifying the relationships between radio signals and extraneous noise, John Carson concluded that "even with absolutely ideal selective circuits, an irreducible minimum of interference will be absorbed, and this minimum increases linearly with the frequency range necessary for signaling." The curtain seemed to have been drawn on FM radio.[5]

Yet in 1936 Edwin Armstrong published a paper on FM radio in the *Proceedings of the IRE* which turned the conventional wisdom on its end. Armstrong's innovation as demonstrated to the IRE in that year proved that his FM system could out-do virtually everything AM systems touted. His system, unlike earlier systems, did not use the existing band of frequencies allocated for AM broadcasting. Instead, he used advanced new transmitting tubes to broadcast FM at much higher frequencies in the 44 megahertz range. Further, Armstrong's system could transmit a signal corresponding to virtually the entire range of frequencies audible to the human ear. This contrasted strongly with the existing AM system which was designed to "cut" the frequencies above about 8,000 Hz. Besides the "high fidelity" potential of this system, the broad-band FM system utilized new types of noise eliminating circuits integrated into the receiver. Thus Armstrong's system not only eliminated almost all static under normal conditions, it possessed standards of fidelity superior even to a static-free AM broadcast. The system demonstrated a high degree of selectivity, making it possible for stations in different cities or areas to broadcast on the same frequencies without interfering with each other's signals.[6]

But how and why had Armstrong invented his novel system in the face of such a negative consensus regarding FM? Why has it proved so successful? The details of this story will await a more thorough historical analysis, but some evidence suggests that part of the success of the FM system was closely tied to Armstrong's style of invention. It could be argued that the development of this successful FM system was somehow intimately tied to a particular style of invention, one that did not rely on convention.

Elements of that style of invention, of course, predated his FM idea. Armstrong's approach to technological innovation before FM, had bucked some of the conventional ideas about engineering. in the 1920s he established a national renown on the basis of the regenerative receiver, a rather elegant circuit design which improved the performance of vacuum tube amplifiers in radio circuits, and pioneered the use of the vacuum tube oscillator. Armstrong's discovery of the regenerative circuit emerged from his study of the recently-invented audion vacuum tube. Troubled by inventor Lee DeForest's vague explanations of just how the audion amplified electrical currents, Armstrong set out to test the audion and determine the true nature of its function. What emerged from this empirical study of the audion was a much more clear, theoretical understanding of the workings of the vacuum tube amplifier, together with a series of circuits designed to exploit its amplifying and oscillation properties.[7]

Armstrong was an outspoken advocate of such empirical studies, and deplored the purely mathematical or theoretical approach to electrical engineering as practiced by John Carson, who attacked FM in the 1920s. Armstrong's style of invention in turn reflected the technique of a number of famous inventors. Historian Eugene Ferguson has noted the importance of one special kind of inventive style in his essay on "spatial thinking." Many successful inventors and scientists, he says, are able to think in a visual fashion, manipulating images in their minds. Such a style of thinking lends itself well to an experimental, empirical approach to engineering but seems incompatible with the more theoretical approach typified by John Carson. Even in electrical engineering, a field of knowledge in which it would seem difficult for the mind to visualize electrical processes, many successful inventors seem to have in fact taken this approach. The work of A. G. Bell on the telephone comes to mind as does the many electrical inventions of Thomas Edison. The memoirs and papers of these inventors clearly show a visual, empirical approach to invention.[8]

Such an approach also made it easier for Armstrong to challenge the conventional wisdom about FM. Carson's damnation of FM, seemingly carved into stone through the publication of his irrefutable mathematical equations, nonetheless rested on a series of not-so-obvious assumptions about radio practice. By incorporating some of the new techniques that had been developed in radio, exploiting the "very high frequency" (VHF) band of frequencies, for example, Armstrong opened up Carson's predictions to question. It seems unlikely that Carson would have changed his underlying assumptions even if VHF broadcasting had been feasible when he wrote, simply because he would have had little intuitive reason to suspect that radio transmission would have been different at VHF in any important way. Rather, the non-mathematical, empirical, and almost necessary "spatial" type of engineering emerges as the most logical way for the FM system to have developed.

A second strength of Armstrong's style regarding development of a commercially-viable FM broadcasting method was his treatment of the innovation as a system. FM is perhaps the greatest of Armstrong's contributions because of the fact that it comprises an entire matrix of innovations, incorporating all of the necessary equipment from transmitter to receiver. His prior inventions, things like the regenerative and superheterodyne circuits, were merely improvements in the components of the existing radio broadcasting service. FM envisioned something more; an entirely new way of broadcasting, encompassing a prescription for a new kind of commercial network based on more stations and the vast technical leap into "high fidelity."

Here again, Armstrong's system approach has similarities with the work of other inventors. Like Armstrong, the strength of Thomas Edison's development of electrical lighting is thought to be connected to the inventor's systems approach. Historian of technology Thomas P. Hughes has written extensively on Edison's system of lighting, and speaks convincingly of the momentum of the system in overcoming competing lighting technologies.[9]

With the demonstrable superiority[10] of FM and the strength of a completely-developed broadcasting system in his favor, Armstrong sallied forth to sell his system to the radio industry. Initially he contacted the Radio Corporation of America to whom he had promised "first refusal" of his inventions. After failing to receive a commitment from RCA president David Sarnoff, Armstrong reinforced his personal role in the development of FM by attempting to promote the technology on his own. He did so by building a radio station that began broadcasting from an antenna in Alpine, New

Jersey in 1938.[11] In promoting his system as a commercial possibility, he ran into three problems almost immediately. FM was designed to utilize a newly-accessible section of the very-high-frequency band (VHF) but it ran against plans, mainly the issue of RCA, to use the same frequencies for television. Secondly, it conflicted with the interests of the entrenched AM industry which, naturally, could not be expected to meet a potentially competitive technology with open arms. Underlying these two politically-oriented objections, Armstrong introduced his system at a time when the U.S. was in the midst of the Great Depression and little capital was available from radio equipment manufacturers for expensive new broadcasting systems. A few brave entrepreneurs established small FM stations between 1939 and the outbreak of the war, and Zenith and General Electric sold FM receivers, but little came of this activity.[12]

Armstrong ceased most of his engineering activities in the 1930s and embarked upon a fierce battle for FM, taking on both the powerhouse of RCA and the industry-dominated Federal Communications Commission. Armstrong's situation as an inventor-entrepreneur was closely modeled after his colleague and mentor at Columbia University, Michael Pupin. Pupin, also an inventor of electrical devices, was with Armstrong, one of the few university faculty members in the U.S. who have become wealthy making inventions. Like Pupin, Armstrong used his university appointment as a way in which to conduct research, and his tenured position allowed him the extended periods of time he needed to pursue patent battles.[13]

Throughout the late 1930s and early 1940s, then, Armstrong and his lawyers fought with RCA and other manufacturers over patent infringements, and pleaded with the FCC for a reasonable set of broadcasting regulations. These hearings and court cases would continue for years, and the last would not be settled until after Armstrong's death. The minutiae of these battles is contained in Don V. Erickson's book *Armstrong's Fight for FM Broadcasting*, which makes a persuasive argument for the pro-industry slant of the FCC commissioners and the duplicity and underhandedness of RCA's executives and lawyers. Additionally, though, Erickson's book documents lucidly the phase of FM's history during which Armstrong's personal direction of events surrounding FM radio began to diminish under the influence of stronger historical trends. In fact World War II, during which FM's commercial development stagnated under the priorities of wartime communications, marks the real turning point in the FM story.[14]

The eventual success of commercial broadcasting had little to do with Armstong's posthumous vindication in the Patent courts or the strength of his arguments to the FCC. Rather, FM fit into a larger pattern of change in communication history. The post-World War II period saw an enormous upheaval in broadcasting technology. AM radio, which had reigned supreme since the early 1920s, now diminished rapidly in importance next to television and, later, FM. When the war ended, the American economy was markedly stronger than it had been in the 1930s, and the general re-conversion of American industry to civilian production brought forth a short-lived boom in consumer spending. Yet several other crucially important factors influenced the rebirth of FM.

When the war ended, the FCC "freeze" on the construction of new radio stations was removed and a spate of new building occurred. Yet almost immediately the industry was jolted by the re-allocation of commercial FM frequencies from the 42-50 MHz range to the 88-108 range, located just above the television spectrum. The FCC justified the move on the basis of concern over the "troublesome skywave interference" of the lower band, but the real impetus probably emerged from the political pressuring of the television equipment manufacturers, notably RCA. Radio equipment manufacturers were now ready to jump on the FM bandwagon, but if this new system of broadcasting was to emerge, it would necessitate a wider band of frequencies to permit more stations to operate simultaneously. Since large companies like RCA could design and supply equipment to work at any viable portion of the radio spectrum, why not pressure the FCC for a new, wider frequency allocation? The independent stations operating elsewhere on the spectrum (who incidentally would be subjected to severe economic hardship by this shift), and the few people who already owned FM receivers could all go hang. For whatever reasons, the FCC eliminated the old FM band and pre-war FM was instantly damned to obsolescence.[15]

Nonetheless, following this setback, a flurry of new interest in FM radio stations emerged and this persisted into the mid 1950s. New stations were built by the score, and a few small networks established service at the new frequencies, including the Yankee Network serving New England, that had pioneered an FM network on the old band in the late 1930s. With the coming of television, however, the bottom dropped out of network radio.[16] Television had the effect of drawing off the large proportion of people who had formerly tuned in to pre-war style programming -- the dramas, comedies and live music shows that had sustained commercial radio for years. A CBS radio executive quoted in 1955 in *Time* magazine lamented that "the silk business had Nylon and we have TV."[17]

A *Newsweek* article asked in 1956: "Is Network Radio Dead?" and cited a diminution in the audience for network radio programming from 25 million before the advent of post-war TV to only 1.5 million in the mid-1950s. Clearly, commercial radio was undergoing violent changes.[18]

Yet these changes benefited the revival of FM. In the early 1950s commercial FM began to suffer the ill effects of a 1948 FCC ruling which allowed for the simultaneous broadcasting of AM programming on FM stations. Advertisers were hard pressed to see the need to pay for time on FM radio when they often could get it for "free" by buying AM time. It was probably the emancipation of network broadcasting and the subsequent reorganization of radio programming which helped free FM of this burden. By the mid-1950s the FCC had reversed itself and committed FM broadcasters to a minimum amount of FM-only programming.[19]

The death of network radio also sent both AM and FM down the programming path they follow now -- a combination of talk shows, sports, news, and pre-recorded music. Ironically, as network programming withered, the number of new radio stations was increasing at a fairly rapid clip. As television shows displaced radio shows, market analyses found that a new kind of radio listening pattern had emerged, characterized by short, intermittent periods of listener attention. Thus, popular music or shows interspersed with advertising at shorter intervals proved more effective for advertisers than the previous convention of longer shows with fewer commercial breaks. Automobile radios also began to be more common after the war, and broadcasters found that more and more of their listeners tuned in for short periods while driving. Thus liberated from the yoke of the national networks, FM stations, especially those broadcasting popular music, began both to proliferate and to make money.[20]

Yet what seems to have cemented FM in the firmament of commercial broadcasting, though ironically it emerged quite late, was the feature of FM most highly touted by Edwin Armstrong in 1933: high fidelity. "Hi-Fi" emerged as a popular fad in the early 1950s, and by the end of the decade was a permanent feature of the expanding consumer electronics industry. The hi-fi movement began in earnest in the post-war period as technically-minded experimenters built and sometimes designed their own radio receivers, amplifiers, and loudspeakers in an attempt to reproduce better-sounding music.[21] Just after the war, the British Decca company introduced a selection of "full-frequency range records" that represented a substantial improvement over what was commercially available elsewhere. Almost simultaneously, a number of small electronic companies began manufacturing hi-fi components in the U.S.; one example being Norman Pickering who developed an enormously successful hi-fi phonograph cartridge. In the late 1940s, German magnetic tape technology began to be used in American recording studios, and combined with the advances in microphones, signal processing, and studio techniques, the use of tape contributed to marked improvement in phonograph record quality. 1948 saw the introduction of the microgroove record which again entailed improvements in fidelity. Interest in hi-fi, "born of solder steam and midnight cursing," became so widespread in the early 1950s that the larger radio and phonograph manufacturers took heed and introduced their own lines of equipment aimed at a new market.[22]

By the early 1950s, popular magazines were touting the virtues of hi-fi to a wider audience. *Atlantic Monthly* pioneered the hi-fi campaign with a monthly hi-fi column early in 1950. As early as 1952 such magazines as *Better Homes and Gardens* and *Life* ran features that gushed about the possibilities of home hi-fi systems. Record reviewer and hi-fi columnist John M. Conly noted in 1954 that much of the credit for what *Time* had called "the hi-fi hysteria" was due to the education of the public who were taught "how to listen" in the hi-fi era. FM fit perfectly into the hi-fi movement, and though FM was neither the cause nor the result of the hi-fi hysteria, its fortunes were enhanced by the emergence of this fad. Though it was not until about the middle of the 1960s that FM broadcasting seemed secure as an industry, it was probably the popularization of hi-fi that contributed most to its success.[23]

Thus some time after World War II, responsibility for the development of FM passed out of Armstrong's hands as cultural and technological trends leading to hi-fi and the modern system of radio broadcasting converged. Armstrong during this period pursued doggedly his patent claims, but after the war these became only a minor adjunct in FM's history. For Armstrong, however, these claims remained the center of his attention. Armstrong's fighting against both the politically-motivated FCC and the behemoth of RCA must have been a bit like bashing one's head against a wall. In 1954 Armstrong could stand it no more and, as the story goes, dressed himself in coat, hat, and gloves, and passed out of the high window of his New York apartment, resulting in his death.

About six months after his tragic suicide (six months being the standard deadline for features in many magazines), Lawrence Lessing eulogized his friend Edwin Armstrong in *Scientific American*. Lessing, a member of the editorial staff of the magazine, followed up this article with his 1956 book entitled *Man of High Fidelity*. This work remains the standard biography of Armstrong as well as the predominant source for the history of FM. Incredibly, though Armstrong's notes and personal papers have been available to historians for years, the admirable but still less than objective book by Lessing has not been challenged by a new interpretation.

It has been the purpose of this article not to revise the findings of Lessing in any significant way but to suggest that the scope of the history of FM is much broader than Lessing's heroic, one-man-fight-against-RCA presentation. It is my hope that this article will provoke new interest in the documentation of FM's history.[24]

FOOTNOTES

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[4] John R. Carson, "Notes on the Theory of Modulation," *Proceedings of the IRE* 10 (1922): 57-64.

[5] John R. Carson, "Selective Circuits and Static Interference," *The Bell System Technical Journal* 4 (1925): 265.

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[7] Edwin H. Armstrong, "Some Recent Developments in the Audio Receiver," *Proceedings of the IRE* 3 (1915): 215-47; Armstrong, "Operating Features of the Audion," *Electrical World* 64 (1914): 1149-52.

[8] Edwin H. Armstrong, "Wrong Roads and Missed Chances: Some Ancient Radio History," *Midwest Engineer* 3 (March 1951) 3-5, 21, 25; Armstrong, "Vagaries and Elusiveness of Invention," *Electrical Engineering* 62 (1943): 149-51; Armstrong, "The Regenerative Circuit," *The Electric Journal* 18 (1921) 153-4; Armstrong, "Mathematical Theory Versus Physical Concepts," *FM and Television* 8 (1944): 11-13, 36; also see Alan Hazeltine's discussion of Armstrong's style given for the presentation of the Edison Medal to Armstrong by the AIEE in 1943 in "E.H. Armstrong -- Edison Medalist," *Electrical Engineering* 62 (1943): 147-149; Eugene Ferguson "The Mind's Eye: Nonverbal Thought in Technology," *Science* 197 (26 August 1977), 827-35; Lessing, *Armstrong* 199-203; Robert V. Bruce, *Bell: Alexander Graham Bell and The Conquest of Solitude* (Boston: Little,Brown and Co., 1973, 120-4; Reese V. Jenkins, et al.,eds.,*The Papers of Thomas A. Edison*, Vol. 1, "The Making of an Inventor: February 1847-June 1873" (Baltimore: The Johns Hopkins University Press, 1989), xxxiv-xxxvii; Michael E. Gorman and W. Bernard Carlson, "Interpreting Invention as a Cognitive Process: The Case of Alexander Graham Bell, Thomas Edison, and the Telephone," *Science, Technology and Human Values* 15 (Spring 1990): 131-64.

[9] Thomas P. Hughes, The Electrification of America: The Systems Builders," *Technology and Culture* 20 (1979): 124-61; also see Robert Freidel and Paul Israel, with Bernard S. Finn, *Edison's Electric Light: Biography of an Invention* (New Brunswick, NJ: Rutgers University Press, 1986), 226.

[10] Contemporary reviews of Armstrong's system by engineers who were overwhelmingly supportive. "Frequency Modulation Advances," *Electronics* 8 (1935): 188-9; Guy Bartlett and Phillips (sic) C. Caldwell, "Highlights and Sidelights," *General*

Electric Review 43 (1940): 425; D. G. F[ink], "Frequency Modulation -- A Revolution in Broadcasting?," *Electronics* 13 (January 1940): 10-14; *FM: An Introduction to Frequency Modulation* (New York: John F. Rider, Publisher, Inc., 1940), iv-v; Raymond F. Guy, "How and Why of Frequency Modulation," *Radio Craft* 13 (July 1941): 25-7; J. E. Brown, "Frequency Modulation and its Post-War Future," *Electronics* 17 (July 1944): 94-9; Th. J. Weijers, "Comparison of Frequency Modulation and Amplitude Modulation," *Phillips Technical Review* 8 (March 1946): 89-96.

[11] Lessing *Armstrong* 218-234; The personal relationship between Sarnoff and Armstrong is the focus of a recent essay by Keiron Murphy, "The Major and the General," *IEEE Potentials* 9 (February 1990): 50-1.

[12] The two Zenith models introduced in 1940 had retail prices of $139.50 and $129.50. The G.E. "Musaphonic model 80" had a retail price ranging from $595-675, depending upon appointments. "Zenith Delivers Two FM Models," *FM* 1 (December 1940): 7, 20; "G.E. FM," ibid., 8-9.

[13] James E. Brittain, "The Introduction of the Loading Coil: George A. Campbell and Michael I. Pupin," *Technology and Culture* 11 (1970) 36-57.

[14] Erickson, *Armstrong's Fight* passim; For a contemporary account, see "The History of Frequency Modulation," *FM* 4 (1944): 28-38; During these years Armstrong played another, less visible role as a leading promoter of commercial FM broadcasting. He was prominent in the activities of FM Broadcasters, Incorporated, an industry group formed in 1939. He wrote several articles in which he railed against the inertia of the established radio industry. The inherent quality of FM transmission that allowed stations to transmit on the same frequency though in relatively close proximity became the basis of Armstrong's promotion of the democratic virtues of FM. "Engineers Discuss FM," *Electronic Industries* 3 (March 1944): 110; Edwin Armstrong, "Frequency Modulation and Its Future Uses," *Annals of the American Academy of Political and Social Science* 213 (1941): 153-61; Armstrong, "Evolution of Frequency Modulation," *Electrical Engineering* 59 (1940): 485-93; Armstrong, "The New Radio Freedom," *Journal of the Franklin Institute* 232 (1941): 213-16.

[15] *FCC Annual Report*, (1946): 16. In fact, the existing stations had until 1947 to cease operating on the old band. It is not clear how many persisted to the end.

[16] "Revolution in Radio," *Fortune*, (October 1936): 86; Another FM network was the Continental Network, inaugurated in March 1947, which served several states in the northeast part of the country. *FCC Annual Report*, (1947): 22.

[17] "The State of Radio, *Time*, (9 May 1955): 70.

[18] "Is Network Radio Dead?," *Newsweek*, (20 August 1956): 61.

[19] *FCC Annual Report*, (1948): 36.

[20] Nat Hentoff, "The FM Boom: Radio for Grownups," *The Reporter*, (May 1958): 31-4.

[21] Many of these early experimenters were vocal in their support of high fidelity and published a number of articles on hi-fi in technical journals. An example is Hugo Gernsback who wrote "The Rising Tide of FM," for *Radio Craft* 19 (June 1948): 17; Edward Tatnall Canby has made a career of writing such articles and currently edits *Audio* magazine. See especially his recent article on his experience in early FM programming, "Time After Air Time," *Audio* 70 (1986): 39-42.

[22] John M. Conly, "They Shall Have Music," *Atlantic Monthly* 185 (March 1950): 91-6; David L. Morton, Jr., "John Herbert Orr and the Building of the Magnetic Recording Industry, 1945-1960," (M.A. Thesis, Auburn University, 1990): 39-40, 59-60; Hi-fi shops sprang up as early as 1950. Concord Radio in Chicago, for example, was one of the early examples of the modern electronic entertainment retail stores. It featured dozens of different brands of audio components, all of which could be tested before purchase in any combination. Concord was decorated with the works of local artists, and the exhibits were changed at regular intervals. "Selling Audio Performance," *FM-TV* 10 (August 1950): 24-8, 32.

[23] "Pleasant Sound," *Time*, 13 (January 1958): 40; John M. Conly, "Hi-fi For All," *Atlantic Monthly* 194 (September 1954): 89-93.

[24] Lawrence P. Lessing, "The Late Edwin H. Armstrong," *Scientific American* 190 (April 1954): 64-9.

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NEW RADIO MARVEL REVEALED IN TEST

Transmitter Power Cut From 20,000 to 5 Watts Without Affecting Reception

STATIC AT A MINIMUM

System Developed by Major E. H. Armstrong Explained to Radio Club

Some of the hitherto unrevealed wonders of the new "frequency modulation" radio broadcast system developed by Major Edwin H. Armstrong Columbia University electrical engineering professor, were demonstrated last night at the university at a meeting of the Radio Club of America.

Assisted by three engineers of the General Electric Company, Major Armstrong was able to show in a series of tests that the transmitting power of his 20,000-watt station at Alpine, N. J., twelve miles up the Hudson, and a similar 600-watt station in Yonkers, could be reduced almost to the vanishing point without appreciably affecting the quality of the program. At the same time this huge reduction in power, about 4,000 times in one case and 600 in the other, respectively, did not seem to cause an increase in static noises.

In other words he purported to show, and seemed to succeed in showing, that with his unique system high-power stations are not necessary for perfect, noise-free reception.

Directing the tests by telephoning to his operators at Alpine and Yonkers, Major Armstrong first showed the several hundred assembled engineers of the club what music and sound effects "sound like" with his system blotting out the noise generally considered inherent with all types of reception. Each sound was crystal clear and life-like, and murmers of approval were heard from the audience.

Music Is Not Affected

He then asked Yonkers to reduce power from 600 to one watt. Music sent over the wave thus created by scarcely as much as is required to light the bulb of a pocket flash lamp, seemed to suffer not a bit by the reduction. Next he instructed Alpine to reduce its 20,000 watts to a minimum, which he said would be five or six watts of power. The result was about the same as with Yonkers.

Major Armstrong then explained to the assemblage that "I believe this demonstration speaks for itself; certainly it tells us the system actually does step outside the realm of static. We have reduced our sending power almost to the irreducible minimum and still have transmitted music of the same quality without appreciably adding noise."

The Alpine station, erected by Major Armstrong to prove his theories that "frequency modulation will work," utilizes a wavelength of about six meters. The Yonkers station, owned and operated by C. R. Runyon, an amateur, utilizes a wave of three meters.

Next, programs were routed over both channels; Yonkers to Alpine to the Pupin Laboratory at Columbia, where the music was reproduced by a battery of loudspeakers. Results were quite as favorable as when only one channel was employed.

To Appease the Skeptical

A number of sound effects also were tried, to appease those among the gathering who still were skeptical. Extremely faithful reproduction of the original sounds were apparent in all cases. The faintest tinkle of water poured into a glass at the sending station could be heard.

The technical side of "frequency modulation," and the results of tests carried out in the past few months with similar stations at Schenectady and Albany were discussed by I. R. Weir, C. W. Fyler and J. A. Worcester, engineers of the General Electric Company. The gist of all the field results, it was said, has been highly in favor of the Armstrong system, compared with other methods.

The two up-State stations were arranged to operate on both the Armstrong method and the usual type of broadcasting, known as "amplitude modulation," to compare each system. Identical powers were used in each case, and the same wave length was employed. Then, with a receiver arranged to intercept either type of broadcasting, the engineers motored along the fifteen-mile Schenectady-Albany road looking for trouble.

When the transmitters were on "amplitude" broadcasting plenty of trouble was found, Mr. Fyler said. The trouble area began a mile out of Schenectady and ended only a mile or so from Albany, he asserted. The waves interacted and caused noise and whistles.

"With the Armstrong frequency method, however, it was a different story," related Mr. Fyler. "Only in an area a mile wide, midway between the two cities, did we encounter trouble, and even in that area we made the new method work perfectly. All we had to do was move the set's antenna rod a half-inch one way or the other and Schenectady came in and Albany was excluded, or vice versa."

New York Times, March 24, 1939.

Evolution of Frequency Modulation

EDWIN H. ARMSTRONG

Embracing the substance of lectures presented before many AIEE Sections and other groups, and particularly of an address delivered at the 1940 AIEE Pacific Coast convention, this article by the inventor indicates briefly how the frequency-modulation system of radio communication differs from the present amplitude-modulation system, traces the history of this new system, points out its advantages over the amplitude-modulation system, and indicates the extent of its probable applications in the future.

SOME 60 years ago the electric-power industry began the development of a system of distribution which all are now agreed was not the right system. I am referring of course to the low-voltage d-c system. The inevitableness of its replacement by the high-voltage a-c system is now obvious to everyone, although the literature of the transition stage reflects a period of violently conflicting opinion.

A part of the radio industry, in fact by far the largest part, is about to pass through a similar transition. It has become obvious that the present system of broadcasting is not the best, and that its faults are readily curable by the introduction of new technical methods. The characteristics of this new system are such as to provide practically perfect solutions of most of the troubles of the present structure.

These faults are, specifically referring to the broadcast industry: the interruption or marring of the transmission by natural (lightning) or man-made static; the inability either to transmit the full musical range because of a lack of available channel space in the frequency spectrum, or to transmit that part which can be transmitted with full fidelity; the drastic mutual curtailment of the service ranges of two stations on the same wave lengths, even though separated hundreds of miles; and the distortion of the reproduction at certain points in the transmission paths by a phenomenon of propagation known as selective side-band fading. These difficulties and disabilities of present-day broadcasting are about to disappear with the introduction of a new system which has become popularly known as "frequency modulation," although much more is involved than a method of modulation per se.[1] Some 15 broadcast stations employing this system are now in operation and some hundreds are projected.

The problems solved are not merely technical ones. Since the system is primarily adapted for use in the ultra-high-frequency part of the spectrum, so much new frequency space becomes practically available that it has become possible to allot channel facilities to every town in the country. The factor that determines whether a community may have a station to serve its local needs is no longer the availability of channel space, but the economic ability of the community to support it. The development of local broadcast service within these smaller communities will play an increasingly important part in the broadcasting of the future.

MODULATION

Modulation in radio signaling is the process of changing some characteristic of the radio wave in accordance with the intelligence to be transmitted. The earliest form of modulation was the interruption or the breaking up of the radiated energy into the long and short pulses of the Morse code by means of a telegraph key, although in those days the term "modulation" was not used. Subsequently, with the introduction of continuous-wave generators, as distinguished from the "damped" wave or spark type of transmitter, it became possible to superimpose the characteristics of the voice or music on the radio wave. The method employed followed closely upon an early form of wire telephone transmission in which the strength of a current flowing through the line was varied in accordance with the tones of the voice, the number of times per second the direct current was "modulated" above and below its normal value corresponding to the frequency of the tone to be transmitted (considering, for example, a single tone), and the magnitude of the change corresponding to its loudness. In the earliest form of radio telephony the strength of the antenna current at the transmitter (in this case alternating several hundred thousand or more times per second) was varied in amplitude by a microphone connected in the path of the current. At the receiver, in the circuits of which currents corresponding in form to those transmitted were flowing, the variations in the amplitude of the high-frequency current were converted by means of a rectifying detector into currents corresponding in frequency and amplitude to those which the microphone would have created were it "modulating" a direct current. These currents may be observed in an ordinary telephone receiver.

The difficulties of handling large antenna currents by either a single microphone or a group of microphones led to various proposals for another form of modulation known then as "wave length" modulation. In this method, the amplitude of the antenna current remained unchanged, but the wave length or frequency was periodically increased above and decreased below a certain resting value,

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[1] For numbered references see list at end of article.

the number of times per second the frequency was swung about the midpoint being determined by the frequency of the tone to be transmitted, and the extent of the change above and below (or the "deviation" from) the mid-frequency point being proportional to the strength or loudness of the tone. It was proposed to effect this kind of modulation at the transmitter by changing the inductance or capacitance of the circuit controlling the frequency of the oscillation generator by means of some electrostatic or electromagnetic microphone. Since no change in amplitude of the radio wave was produced, the transmission could not be received by the ordinary means. It was proposed to effect reception of waves with this type of modulation by causing the changes in frequency in the received wave to produce changes in amplitude by the use of mistuned selective circuits so that as the incoming variable-frequency current came closer into or receded farther from the resonant frequency of the selective circuit, the amplitude of the currents therein would be correspondingly varied and so could be detected by the usual rectifying means. No practical success attended these proposals, and the literature attests the fact that the early art struggled on with amplitude modulation. About 1914 the advent of the vacuum-tube modulator so completely solved the problems of amplitude modulation that for almost a decade frequency modulation was forgotten.

In 1922 the possibility of its use as a means of reducing the band width required to transmit a given range of frequencies was examined mathematically by Carson[2] who dispelled the illusion that a saving in spectrum space could be obtained over that required by the amplitude-modulation method. Carson proved that at least the same and usually a greater space was required by the frequency-modulation method. Other conclusions unfavorable to the frequency-modulation method were reached. The principal conclusions were subsequently confirmed by other mathematical treatments.

"STATIC"

The major problem of radio signaling for about 30 years has been the interference caused by various forms of natural and man-made electrical disturbances. While radio communication has always been subject to disturbances during lightning storms, the introduction of the vacuum-tube amplifier and the regenerative circuit in 1912 made the problem an ever-present one, as almost any signal could be received, however weak, provided it could be separated from the disturbing impulses which likewise, however weak, were always present. With the coming of broadcasting, which brought the location of the receiving system into areas where high levels of "man-made static" existed, and with the improvements in the sensitivity of the receivers themselves, which finally reached a point where fluctuations in the flow of electrons in the early stages of the amplifier circuits became capable of producing disturbances, the noise problem became the all-pervading one in the art.

Realization of the nature of the problem by those engaged in its study developed slowly. Following the introduction of the new methods of reception in 1912, a vast amount of work was done on the theory that the disturbing waves of natural origin were different in kind from those used in signaling and that circuit arrangements could be devised to differentiate between them. The patent literature of the art of this time furnishes an illuminating illustration of the amount of ingenuity that can be exercised along lines of unsound theory.

It was finally realized that the nature of these disturbances is that of a spectrum which contains all component frequencies, some of which always coincide with those being used in any particular case for transmitting the signal. Carson placed the matter on a quantitative basis in 1925.[3] Subsequently it was shown that many of the man-made disturbances are similar in make-up to those of natural origin and finally that the constitution of the disturbances originating in the irregularities of the motion of the electrons in tubes and circuits is likewise that of a spectrum. The amount of energy absorbed by any electrical system subjected to disturbances of this character depends on the width of the frequency band passed by the selective circuits of the system. Consequently it became a principle of design to make the admittance band of a receiver just sufficiently wide to pass the frequency components necessary to convey the signal, and no wider. The presence of the residual noise came to be accepted as a necessary evil.

Subsequent to the publication of the 1925 Carson article,[3] it occurred to the writer that the use of a system of signaling in which only changes in frequency of a transmitted wave could be observed in a receiver (which was made nonresponsive to amplitude changes) might furnish a means of distinguishing between the desired and undesired currents. An experimental investigation under actual working conditions using a receiver provided with a device for limiting out amplitude changes led to the conclusion that the currents set up in the receiving system by the waves of natural origin were modulated in frequency as well as in amplitude and that no major improvement could be thus effected. These observations were made with the frequency band width of the transmission and reception kept to the narrowest possible limits.

During the course of this work, however, an observation was made which seemed to indicate that the changes in frequency of the disturbing currents were limited in extent. This suggested the idea that if the transmitted wave were modulated widely in frequency and if the receiver were made nonresponsive to amplitude changes, feebly responsive to small changes in frequency, and fully responsive only to the wide frequency changes of the signal, a means of differentiating between desired and undesired currents might be found. With this relatively crude conception of a possible solution the necessary experimental work was undertaken. It resulted in the discovery of a new principle in noise reduction, the application of which furnishes an interesting conflict with the principle that had been the guide to the art for years. In accordance with this principle it was found that in a frequency-modulation system which is not responsive to amplitude changes within its working limits (noise not greater than one-half the signaling current), the wider the band used in trans-

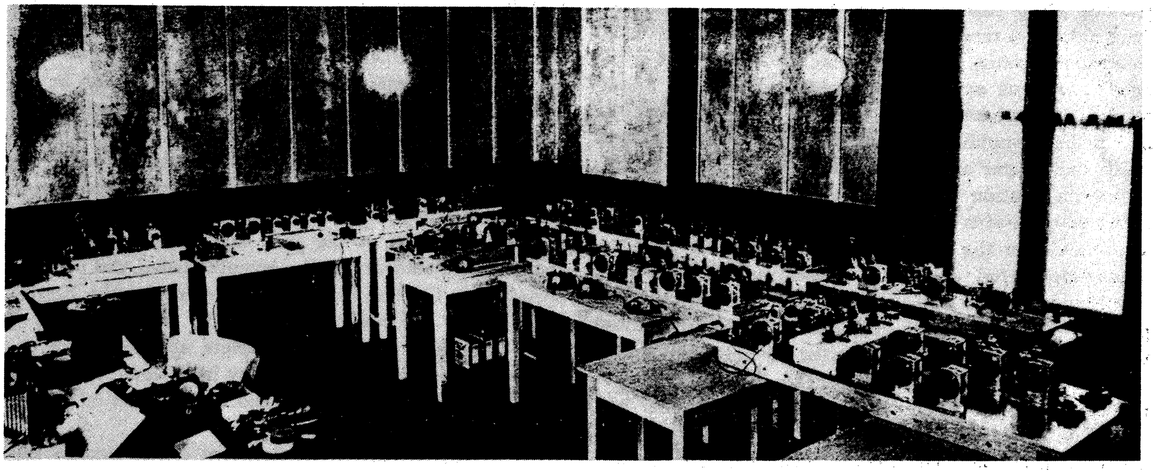


Figure 1. Frequency-modulator setup in shielded room used in early experimental work

mitting the signal the better the signal-to-noise ratio. The power gain of the signal-to-noise ratio increases as the square of the frequency band width used, and gains of a thousandfold or more can be realized in practice. Now the actual mechanism of the process by which the gain is achieved is much more involved than the foregoing explanation would indicate. It may be treated in various ways, but it is beyond the scope of this article to examine it in detail. A full explanation may be found in the writer's paper[1] presented before the Institute of Radio Engineers in 1935. The recent AIEE paper by Everitt likewise contains a detailed explanation.[4] Further reference to this process will be made hereinafter.

TRANSMITTING AND RECEIVING METHODS

In order to carry out the experimental investigation just mentioned, it was necessary to produce both transmitting and receiving equipment. An extensive experience with the known methods of obtaining frequency-modulated signals and their shortcomings led to the development of a new method which gave a complete solution to the problem of producing large frequency changes of a carrier at the relatively high frequencies where of necessity the new system had to operate in order to find available channel space. This method consists in employing the modulating current to shift the phase of a current derived from a source of fixed phase and frequency (usually about 200 kilocycles) by an amount directly proportional to the amplitude of the modulating current and inversely proportional to its frequency. The resulting phase shift is then multiplied several thousandfold by means of a series of frequency multipliers. By keeping the initial phase shift below 30 degrees substantial linearity can be obtained. Some three to five thousandfold multiplication is required in order to give an over-all frequency swing of 150,000 cycles at a transmitting frequency of 40 megacycles. Since it is desirable to perform the initial phase-shifting operation at a frequency of the order of 200,000 cycles the multiplication is carried out in two stages. The first stage usually converts its 200-kilocycle input to 12.8 megacycles; this frequency then is heterodyned with a frequency differing from 12.8 megacycles by a submultiple of the frequency which it is desired to transmit. Where the transmitter frequency is of the order of 40 megacycles the submultiple frequency may be of the order of 600 to 900 kilocycles. This current is then passed through a second series of multipliers until the desired output frequency is obtained, where its power is increased to any required amount by a series of amplifiers.

The receiving equipment follows amplitude-modulation

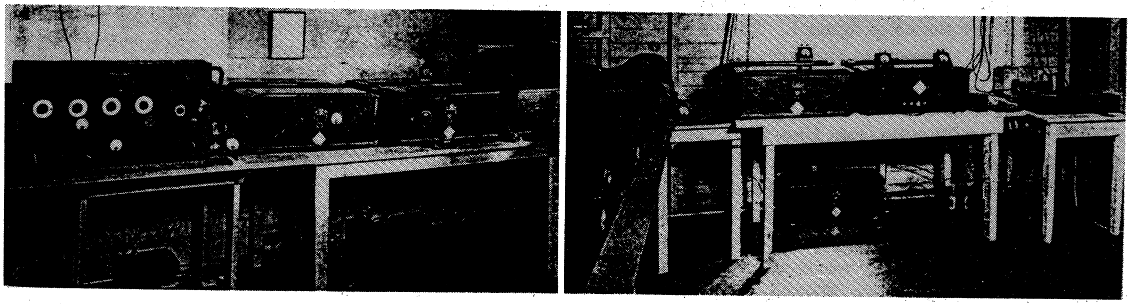


Figure 2. Early experimental frequency-modulation receiving equipment

practice along certain general lines. The superheterodyne method of reception is employed with two additional pieces of apparatus. The first detector or converter of the superheterodyne and the intermediate-frequency amplifier follow standard practice with the exception that the intermediate amplifier has a much broader frequency-band width and greater amplification than in the ordinary amplitude-modulation system. One of the two additional pieces of apparatus is a device for removing changes in amplitude from the received wave so that only pure frequency-modulated current is passed on for detection. This device is generally an overloaded vacuum-tube amplifier in which the screen and plate voltages are reduced to cause the tube to give a limited output; hence it is commonly referred to as a "limiter". It is connected to the output of the intermediate-frequency amplifier and usually requires several volts to be applied to its grid for effective operation. The second device is an arrangement of circuits in which the transmission characteristics with respect to frequency vary linearly over the range of the intermediate frequency through which the signal sweeps. It is placed after the limiter and before the detector, and its function is to convert the frequency changes linearly into amplitude changes. The name "discriminator" is commonly applied to this kind of device. Usually a differential or balanced type of detector is employed.

FIELD TESTS

The many years of research required to test out the principle were carried out in the Marcellus Hartley Research Laboratory at Columbia University, New York, N. Y. Since both ends of the system of necessity had to be under simultaneous observation, the transmitting and receiving equipment were located in adjoining rooms, the distance over which signals were transmitted being some 50 feet. During the winter of 1933–34 the system was demonstrated in the laboratory to the executives and engineers of the Radio Corporation of America for several months. Laboratory experiments in the "static eliminator" field being subject to quite justifiable suspicion, the transmitting equipment was removed from Columbia in the spring of 1934 and installed at the National Broadcasting Company's station located at the top of the Empire State Building in New York. This station had a 2-kw 44-megacycle transmitter which was originally intended for television, but which was not in use at the time. It was modified so as to transmit the wide-band frequency-modulation signals. Two modulators of the type heretofore described are shown in figure 1. They were located in a shielded room adjacent to the power-amplifier equipment and hence could be operated in the open as shown. The receiving system was located at Westhampton Beach, Long Island, about 70 miles from New York City. Figure 2 shows the receiving equipment as installed there in June 1934. The excellence of the results obtained in the initial tests surpassed all expectations, perfectly quiet reception being secured through the heaviest thunderstorms when all the standard broadcast services had been rendered utterly useless. As Westhampton Beach was obviously too favorable a site, the receiver was removed in July to Haddonfield, N. J., near Camden, a distance of about 85 miles from New York, where successful operation likewise was obtained.

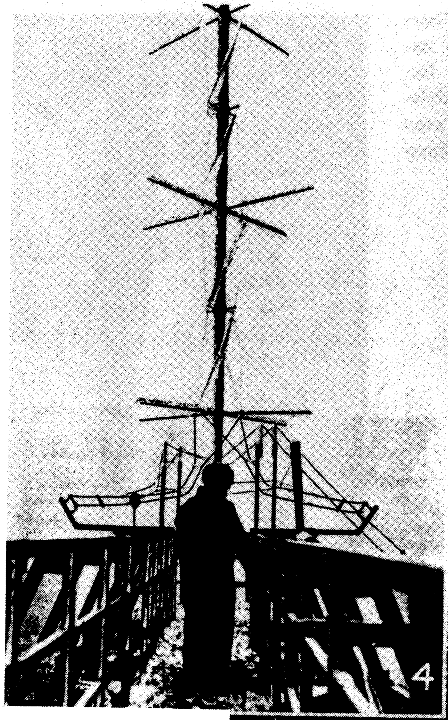
In all these tests much greater improvement in the signal-to-noise ratio was obtained than the thousandfold gain heretofore referred to, as in addition to the improvement due to the use of frequency modulation much less static is encountered on the ultrahigh frequencies than in the standard broadcast band. A pleasant surprise was the establishment of the fact that ultrahigh-frequency transmission, contrary to the accepted belief, did not stop abruptly at the horizon (about 45 miles for the Empire State tower) but could be successfully received up to at least three horizons. The complete absence of all the effects of selective side-band fading from which the standard band suffers was proved, and all the fears of limited coverage were set at rest.

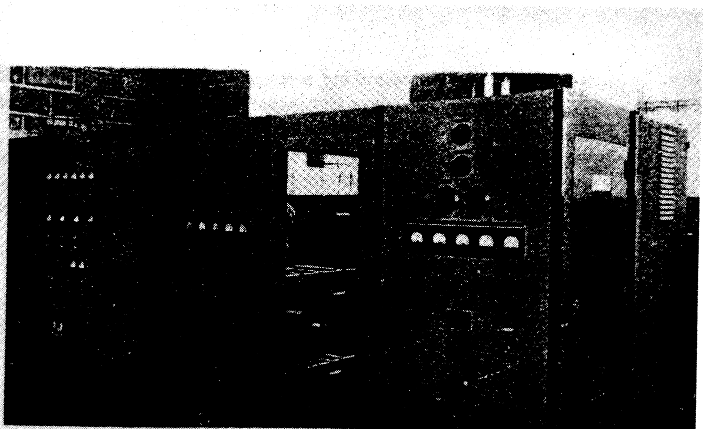
Up to this point the development of the system had proceeded in a normal way, similarly to the pattern followed in the introduction of many other inventions into American radio. However, numberless objections began to be raised regarding the utility of the new system; and although for over a year and a half tests were conducted under all conceivable conditions and repeated demonstrations and comparisons with the existing broadcast system carried out, the Radio Corporation declined to put the invention into public use. The Empire State transmitter was withdrawn from further frequency-modulation tests.

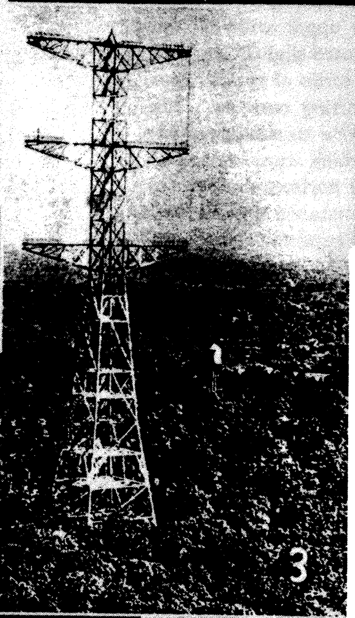
Work therefore was transferred to an amateur station W2AG located in Yonkers, N. Y. This station was equipped by its owner, C. R. Runyon, to operate on 110 megacycles and was used to demonstrate the system to the Institute of Radio Engineers in November 1935, on the occasion of the presentation of a paper[1] describing the system.

Next, application was made to the Federal Communications Commission for permission to construct a high-power 40-megacycle transmitter the success or failure of which would remove from the realm of academic discussion all questions concerning the efficacy of the system. The necessary authoritv was obtained at the end of 1936 and construction was started in the spring of 1937. The erection was completed and testing started in the fall of 1938. In the intervening time scores of demonstrations carried out from the Yonkers station, W2AG, were made to the representatives of the broadcast industry. As a result of these the Yankee Network decided to enter the field and proceeded with the construction of a station near Worcester, Mass. (Mt. Asnebumskit, Paxton). At about the same time, the management of Station WDRC at Hartford, Conn., entered the field with the erection of a station on Meriden Mountain, Meriden, Conn. Shortly thereafter the General Electric Company, as a result of the W2AG demonstrations, became interested and carried out and published the results of a long series of tests confirming the conclusions arrived at during the Empire State field tests.

The Alpine transmitter was ready for preliminary testing during the summer of 1938. All expectations were more than fulfilled and in the summer of 1939 the sta-

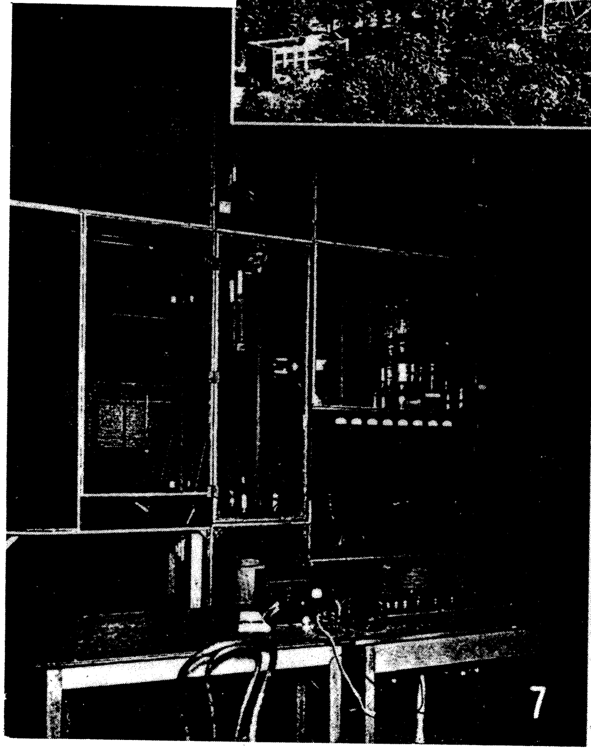


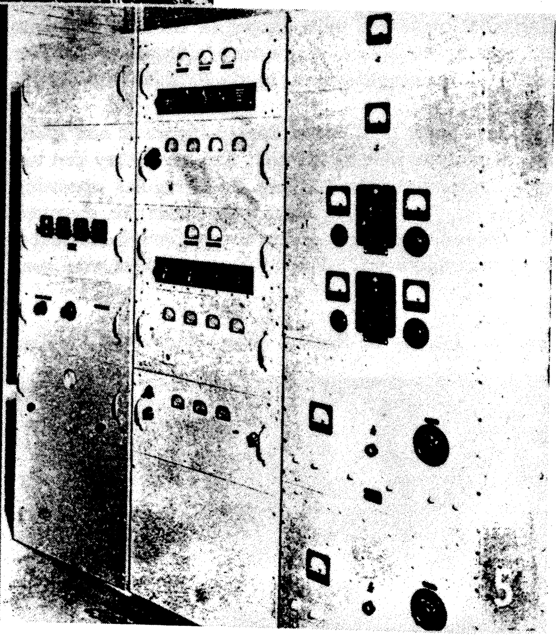




Figures 3–6. Frequency-modulation transmitter built at Alpine, N. J., by the author during 1937–38; note antenna between extremities of two upper arms (3); antenna structure, after a sleet storm (4); modulating equipment (5); frequency multipliers and low-power amplifiers (6)

Figure 7. Last two power - amplifier stages





tion was placed on a regular operating schedule. A general idea of the transmitter as originally installed is given by figures 3 to 7. Since height above the surrounding terrain is of primary importance in ultrahigh-frequency transmission, the site selected was on the cliffs on the west side of the Hudson River known as the Palisades. A point about 500 feet above the river 17 miles north of New York in the village of Alpine was chosen. The antenna structure of the Alpine station is illustrated in figures 3 and 4. The height of the tower above grade is 400 feet. The length of the three cross arms is 150 feet and their vertical separation slightly over 80 feet. The radiating members of the antenna consist of a series of seven pairs of crossed rods about 11 feet long which are mounted on a boom supported between the tips of the two upper arms. These crossed rods or "turnstiles" are separated slightly less than half a wave length and are fed by a series of transmission lines which wind around the supporting member. The whole antenna is fed by an open-wire transmission line of about 500 ohms impedance which runs vertically through the center of the tower and horizontally over to the transmitter building for a total distance of about 700 feet. The efficiency of transmission appears to be of the order of 90 per cent.

The modulating equipment, similar in type to the "bread board" setup of figure 1, is shown in figure 5. The modulator is entirely contained in the center rack, the left-hand rack housing the ordinary line amplifiers, and the right-hand rack housing the power-supply equipment for operating the modulator and other units. Figure 6 shows a further series of frequency multipliers and low-power amplifiers for raising the power to a level of 1 kw at 40 megacycles. The last two power stages employ water-cooled tubes which raise the power respectively to 3 kw and to 40 kw. Figure 7 shows these amplifiers as installed in a shielded cage, which is necessary for the protection of the operating staff from the high field strength. The modulating and low-power units shown in these illustrations were built by the Radio Engineering Laboratories and the two high-power amplifier units by the RCA Manufacturing Company.

In the summer of 1939 the Paxton (figure 8) and Meriden transmitters were completed; and when they and the Alpine transmitter were placed on a regular operating schedule so that their performance could be observed daily, the broadcasting industry became convinced that a change was imminent. A dozen more stations were constructed and applications for over 150 more were on file with the Federal Communications Commission by the fall of 1939, when it was alleged that improper standards were being employed and that a band width narrower than 200 kilocyles could be employed more effectively. The granting of further construction permits was suspended pending an investigation by the Commission of this question and the question of providing additional channel space to accommodate the large number of applications for licenses. A public hearing by the Commission in March 1940, resulted in the approval of the 200-kilocycle band, the rearrangement of the allocation plan to increase substantially the assignment of channel space (42–50 megacycles) and the decision to grant commercial licenses. The Communications Commission has now resumed the issuance of licenses, and some 15 permits for commercial instead of merely experimental operation, have now been granted.

Figure 8. Interior of Paxton, Mass., transmitter building

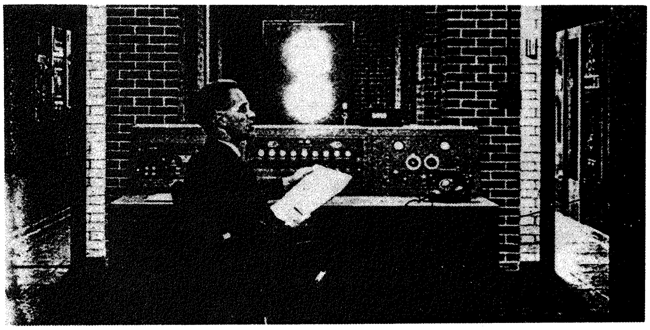
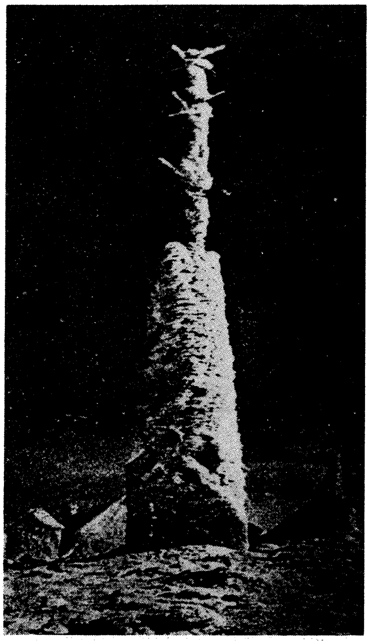


Figure 9. Winter condition of experimental frequency - modulation antenna atop Mount Washington, N. H.



RELAYING

At the present time the wire-line facilities available for linking radio stations into networks are limited to the transmission of a frequency range up to about 5,000 or 6,000 cycles and have a residual noise level considerably greater than that required for the full dynamic range of even ordinary studio orchestral productions. Approximately the same limitation is imposed on the present-day radio stations by the lack of available frequency space and by the noise problem which results when receiver circuits and speaker systems are adapted to reproduce the full audio range of 15,000 cycles. These limitations are not imposed on the frequency-modulation system since the band width used is much in excess of the range of frequencies to be transmitted and the low noise level permits the effective reproduction of the weakest overtones. Residual noise in the transmitting equipment is now better than −70 decibels, so that the signal-to-noise ratio over a large part of the service range of a high-power station can be held below this level. Since the bottleneck, at the present time and perhaps for a long time to come, lies in the wire connecting links, various radio relaying projects have been started.

The first of these was initiated by the Yankee Network to transmit the programs originating in its Boston studios to the top of Mt. Asnebumskit. The air-line distance is approximately 45 miles. Preliminary estimates of the cost of construction of the type of wire line required were in the neighborhood of $70,000, with doubtful guarantees of the noise level. The problem was solved by the use of a frequency-modulated 250-watt 130-megacycle transmitter located on the roof of the six-story studio building, arranged with a directional antenna to beam the transmission toward Paxton. At the receiving end a directional array likewise adds to the efficiency of the circuit.

The initial cost of the installation was a fraction of the estimated cost of the line, its maintenance cost is negligible, and its performance far better than could be obtained with any line facilities that could be furnished, even at the cost mentioned. The circuit has been in operation for over a year and has functioned perfectly through even the heaviest thunderstorms. Experience with this circuit has indicated ways of cutting the cost markedly. A second relay project which the Yankee Network is carrying out is the construction of relay stations to rebroadcast the Paxton transmissions. The first of these to be erected is located at the summit of Mt. Washington in northern New Hampshire, about 130 miles from Paxton. For over six months of the year the climate at the summit of this mountain is one of the severest in the world, winds of over 200 miles an hour with extremely low temperatures being frequently encountered together with a type of ice formation that imposes great mechanical stresses on the antenna structures. Two years ago a 100-foot tower was erected and a small transmitter installed to determine the practicability of the operation of ultrahigh-frequency transmission from an antenna the normal winter condition of which is shown in figure 9. Two winters' experience has resulted in a solution of the problems involved and a one-kilowatt frequency-modulation transmitter is now installed on the mountain (to be increased to ten kilowatts in the spring); regular operation will begin about November 15. The performance of this station will be watched with much interest throughout the radio world. A similar station located on a mountain in northern Vermont will complete the coverage of the northern half of New England. Several similar networks are projected in the southern Atlantic and the Pacific Coast states.

Another relaying circuit is now in daily operation between Alpine, N. J., and Meriden Mountain, Conn., and Alpine and Helderburg Mountain, N. Y., the station of the General Electric Company near Albany. The distances involved are about 70 and 130 miles, respectively. At the Helderburg station reception is effected in the ordinary way, and the recovered audio signaling current at a remotely located receiver is sent over a telephone line to the transmitter where remodulation occurs in the ordinary manner. At the Meriden station the 42.8 megacycles of the Alpine transmission is converted to the Meriden frequency of 43.4 megacycles and amplified up to excite the final power amplifier without the necessity of creating any audio-frequency current in the process. It has been found possible to do this with the receiving antenna located within 100 feet of the transmitting antenna, and the elimination of the processes of detection and remodulation has resulted in the removal of the distortion incident to these operations.

The future undoubtedly will see the introduction of chains of relaying stations equipped with highly directional antenna arrays operating on frequencies considerably higher than those used in broadcasting.

TRANSMITTING AND RECEIVING EQUIPMENT

Great improvement and simplification has been effected in the design of both transmitting and receiving equipment since the building of the initial transmitter at Alpine. It has been found possible to eliminate the intermediate water-cooled power stage and to drive the final 50-kw amplifier directly by a 2-kw air-cooled amplifier stage, this in turn being driven by a pair of 250-watt high-amplification beam tubes, all operating on 40 megacycles. The beam tubes are readily driven by a pair of triplers operating with a power output of 10 to 20 watts. Perfectly stable and reliable operation is obtained with this arrangement of the exciter stages. Figure 10 shows a complete modulating and exciter unit (2 kw). Figure 11 shows the 50-kw amplifier unit for the Paxton station during construction. These units together with the power-supply racks for the high-power amplifier are all that is required for the production of 50 kw of frequency-modulated power.

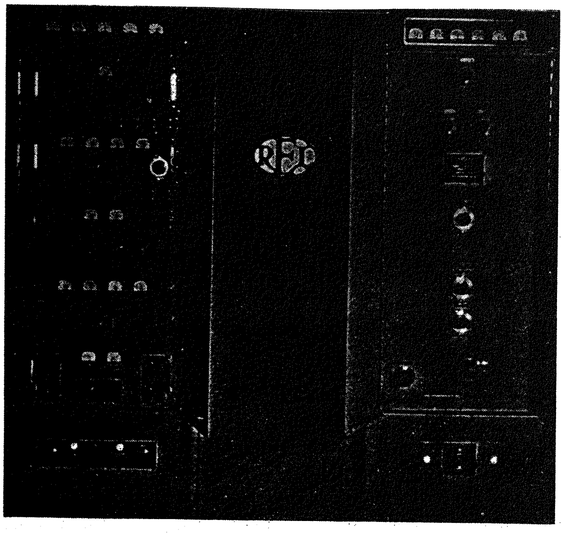


Figure 10. Modulating and power amplifier units of complete two-kilowatt transmitter

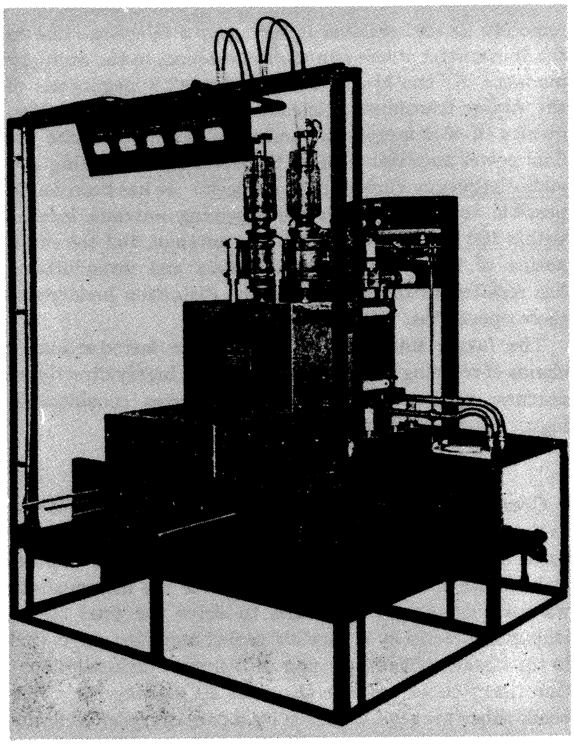


Figure 11. Power-amplifier unit of 50-kw frequency-modulation transmitter before mounting in shielded room

Similar progress has been made in receiver design, figure 12 showing a general-purpose receiver which operates effectively on a field strength of about ten microvolts per meter and gives an undistorted audio output of about 15 watts (a few watts only is necessary for home reception). Ten tubes are used, but with the production of double-purpose tubes specially designed to meet the requirements of this type of receiver further reduction in the number of tubes and parts is possible.

At the present time intensive commercial development of both transmitting and receiving equipment is under way, the General Electric Company and the Western Electric Company being now in position to supply transmitters and some dozen receiver manufacturers having on the market sets adapted to receive both the frequency-modulation and standard-broadcast amplitude-modulation transmissions.

SOME UNIQUE CHARACTERISTICS

There are some characteristics that are unique in the frequency-modulation system which have no counterpart in amplitude modulation. It is, of course, well known that when the carriers of two amplitude-modulated transmitters are sufficiently close in frequency to produce an audible beat, the service range of each of them is limited to that distance at which the field strength of the distant station becomes approximately equal to one per cent of the field strength of the local station. As a consequence, the service area of each station is greatly restricted; in fact, the service area of the two stations combined is but a small percentage of the area rendered useless for that frequency by the presence thereon of the two interfering stations.

With the wide-band frequency-modulation system, however, comparable interference between two transmissions does not appear until the field strength of the interfering station rises to a level of between 25 and 50 per cent of the field strength of the local one. The reason for this lies in the fact that while the interfering signal, in beating with the current of the local station under such conditions, may be producing a large change in the amplitude of the voltage applied to the current limiter, the system is substantially immune to such variations in amplitude. The only way in which the interfering signal can make its presence manifest is by superimposing some modulation of frequency on the frequency variations of the local signal. Under the conditions this "cross modulation" or phase shift superimposed upon the signaling current is limited to something of the order of a 30-degree change in phase, and the characteristics of the wide-band receiver are such that at least within the range of best audibility a phase shift of thousands of degrees in the signaling current is necessary to produce full modulation. Hence the 30-degree interfering phase shift superimposed upon the signaling current will produce little change in the rectified or detected current. As a consequence, the interference area in territory served by two frequency-modulation stations on the same channel is greatly reduced, as compared with amplitude modulation, and becomes, in fact, less than the area usefully served.

This property of the system, coupled with the fact that the propagation limits of ultrahigh frequencies are more sharply defined than those of the present broadcast frequencies, makes it possible to operate stations occupying the same channel space with much less geographical separation. Where desirable, it will be found practical to operate stations from 25 to 50 miles apart.

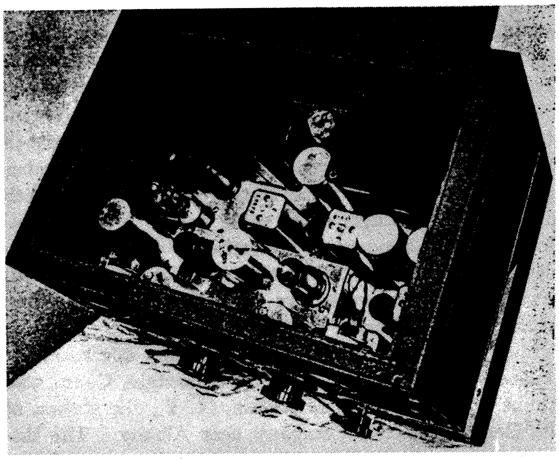


Figure 12. General-purpose frequency-modulation receiver having an undistorted audio output of about 15 watts

There is likewise a fundamental difference in the factors that govern distortion in the amplitude- and frequency-modulation equipment. Provided the circuit constants are properly designed for the frequency of the signaling currents, distortion in an amplitude-modulated transmitter or receiver depends principally on the linearity of the characteristics of the vacuum tubes employed. In frequency modulation, distortion is practically independent of the linearity of all the tubes that handle radio-frequency current and is dependent only on the phase shift introduced by the circuit components. These can be more readily designed and maintained to keep distortion below a desired limit. As a consequence, not only can aural effects be transmitted and reproduced with great fidelity, but the system is well adapted for multiplexing. It has been found possible to transmit simultaneously both an aural and facsimile program without interference between the two, the facsimile transmission being carried out on a channel of superaudible frequency. This was accomplished as early as 1934 over a distance of 85 miles in the original tests using the two-kilowatt transmitter at the Empire State Building in New York.

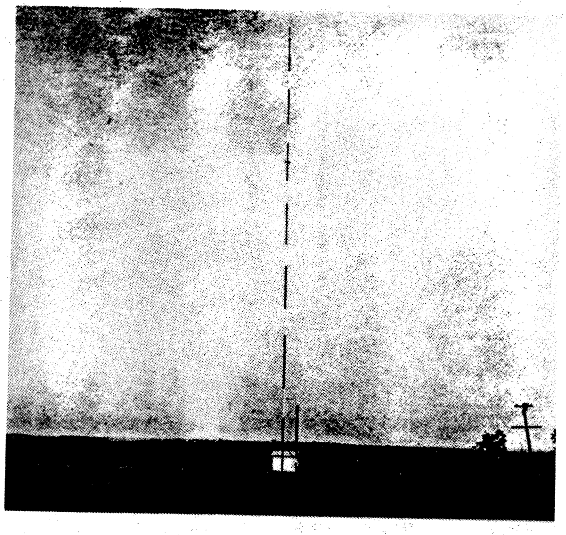


Figure 14. Connecticut State Police system: two-way 250-watt station at Wilton, Conn.

APPLICATION TO SERVICES OTHER THAN BROADCASTING

The system has important applications to various types of emergency communication services. Since the transmission of intelligible speech requires a much smaller range of frequencies than the full musical range—in fact a range of perhaps only 250 to 3,500 cycles—a smaller deviation of the transmitted frequency may be employed. It has been found practicable to make use of a total band width of 40 kilocycles in police service, and several installations are now operating effectively.

The largest project at the present time is that undertaken by the Connecticut State Police, who have in operation nine fixed stations and approximately 200 mobile stations equipped for two-way operation. The fixed stations are located on hill tops and have 250 watts power output. The car transmitters have approximately 25 watts power output. Thirty-mile communication between the cars and the fixed stations and five- to ten-mile communication between cars is easily obtained. This system was designed by Professor Daniel E. Noble (A'32) of the University of Connecticut. (See figures 13 and 14.)

The next largest project to be undertaken is in the city of Chicago, where some 200 mobile 25-watt car units are being installed. Numerous other projects for police services and for emergency-service use by power companies are being made, and it is doubtful if many new installations employing amplitude modulation will be made in the future. It is, of course, needless to say that there are many important military uses. In fact, in practically all ultrahigh-frequency applications where weight or portability is not too great a factor, the frequency-modulation system has found increasing use. The one important field where progress has been inexplicably slow has been television, where its advantages, particularly on the sound channel, could be effectively utilized. A limited use has been made in the relaying of the television sight channel.

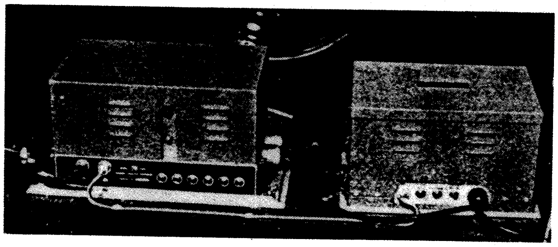


Figure 13. Transmitter (left) and receiver in rear interior of car, Connecticut State Police system

CONCLUSION

Five years ago the writer said[1] that "the conclusion is inescapable that it is technically possible to furnish a broadcast service over the primary areas of stations of the present-day broadcast system which is very greatly superior to that now rendered by these stations." With the cost of transmitting equipment for the new system already below the cost of the equipment of the standard broadcast type (for the same power output) and with the cost of broadcast receivers approaching levels that will permit large-scale production and distribution, the conclusion is likewise inescapable that within the next five years the existing broadcast system will be largely superseded.

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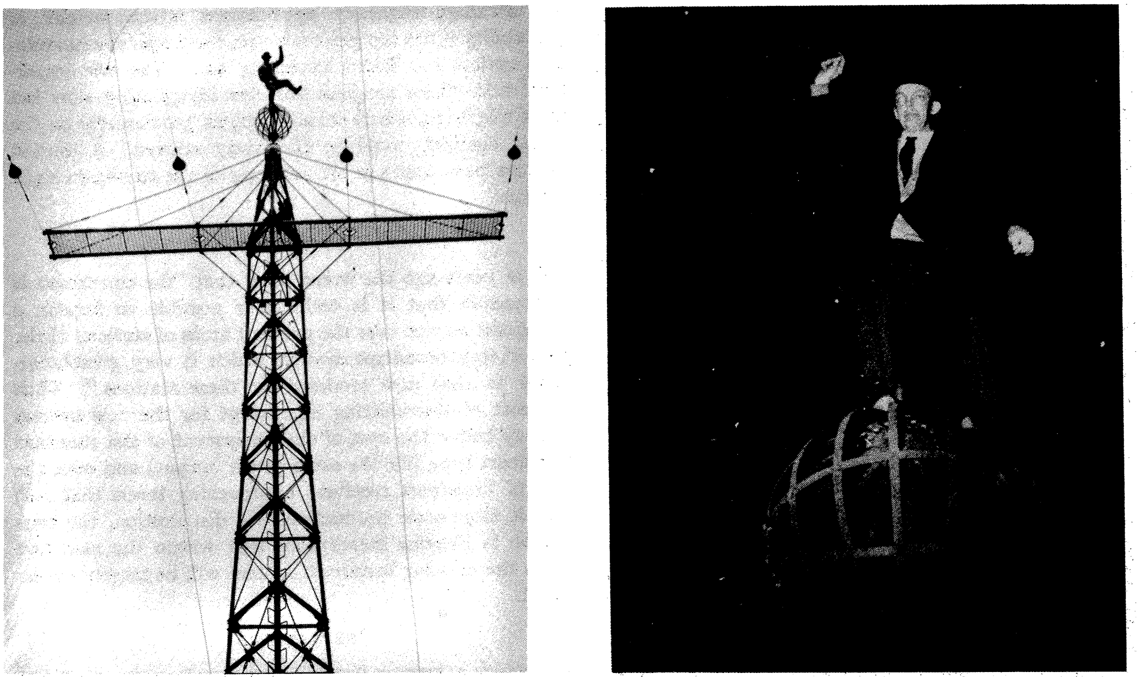
1. A METHOD OF REDUCING DISTURBANCES IN RADIO SIGNALING BY A SYSTEM OF FREQUENCY MODULATION. E. H. Armstrong. *Proceedings* Institute of Radio Engineers, volume 24, May 1936, page 689.

2. NOTES ON THEORY OF MODULATION. J. R. Carson. *Proceedings* Institute of Radio Engineers, volume 10, February 1922, page 57.

3. SELECTIVE CIRCUITS AND STATIC INTERFERENCE. J. R. Carson. *Bell System Technical Journal*, volume 4, 1925, page 265.

4. FREQUENCY MODULATION. W. L. Everitt. AIEE TRANSACTIONS (November section), volume 59, 1940, pages 613–25.

Major Armstrong shown in the attic room of his family residence on Warburton Ave. in Yonkers N. Y. where he made some of his greatest discoveries. The picture was taken about 1950.



Armstrong standing on top of the ball on the antenna tower of RCA Broadcasting Station WJZ, Aeolian Hall, 42nd Street, N. Y. C., 400 feet above the street, in May 1923. WJZ was the first broadcasting station in New York City proper and the pictures were taken just before the opening ceremonies began. As a result of this stunt Gen. Mgr. Sarnoff declared the roof permanently "off limits" for Armstrong.

A METHOD OF REDUCING DISTURBANCES IN RADIO SIGNALING BY A SYSTEM OF FREQUENCY MODULATION

By **Edwin H. Armstrong**
Department of Electrical Engineering,
Columbia University, New York

Presented before The Institute of Radio Engineers, New York, November 6, 1935
Originally published in the *Proceedings of the IRE*, Vol. 24, no. 5, pp. 689 - 740, May 1936

Summary -- A new method of reducing the effects of all kinds of disturbances is described. The transmitting and receiving arrangements of the system, which makes use of frequency modulation, are shown in detail. The theory of the process by which noise reduction is obtained is discussed and an account is given of the practical realization of it in transmissions during the past year from the National Broadcasting Company's experimental station on the Empire State Building in New York City to Westhampton, Long Island and Haddonfield, New Jersey. Finally, methods of multiplexing and the results obtained in these tests are reported.

PART I

It is the purpose of this paper to describe some recent developments in the art of transmitting and receiving intelligence by the modulation of the frequency of the transmitted wave. It is the further purpose of the paper to describe a new method of reducing interference in radio signaling and to show how these developments may be utilized to produce a very great reduction in the effects of the various disturbances to which radio signaling is subject.

HISTORICAL

The subject of frequency modulation is a very old one. While there are some vague suggestions of an earlier date, it appears to have had its origin shortly after the invention of the Poulsen arc when the inability to key the arc in accordance with the practice of the spark transmitter, forced a new method of modulation into existence. The expedient of signaling (telegraphically) by altering the frequency of the transmitter and utilizing the selectivity of the receiver to separate the signaling wave from the idle wave led to the proposal to apply the principle to telephony.

It was proposed to effect this at the transmitter by varying the wave length in accordance with the modulations of the voice, and the proposals ranged from the use of an electrostatic microphone associated with the oscillating circuit to the use of an inductance therein whose value could be controlled by some electromagnetic means.

At the receiver, it was proposed to cause the variations in frequency of the received wave to create amplitude variations by the use of mistuned receiving circuits so that, as the incoming variable frequency current came closer into or receded farther from the resonant frequency of the receiver circuits, the amplitude of the currents therein would be correspondingly varied and so could be detected by the usual rectifying means.

No practical success came from these proposals and amplitude modulation remained the accepted method of modulating the arc. The various arrangements which were tried will be found in the patent records of the times and subsequently in some of the leading textbooks.[1] The textbooks testify unanimously to the superiority of amplitude modulation.

Some time after the introduction of the vacuum tube oscillator, attempts were again made to modulate the frequency and, again, the verdict of the art was rendered against the method. A new element, however, had entered into the objective of the experiments. The quantitative relation between the width of the band of frequencies required in amplitude modulation and the frequency of the modulating current being now well understood, it was proposed to narrow this band by the use of frequency modulation in which the deviation of the frequency was to be held below some limit, for example, a fraction of the highest frequency of the modulating current. By this means an economy in the use of the frequency spectrum was to be obtained. The fallacy of this was exposed by Carson[2] in 1922 in the first mathematical treatment of the problem, wherein it was shown that the width of the band required was at least double the value of the highest modulating frequency. The subject of frequency modulation seemed forever closed with Carlson's final judgment rendered after a thorough consideration of the matter, that "Consequently this method of modulation inherently distorts without any compensating advantages whatsoever."

Following Carson a number of years later, the subject was again examined in a number of mathematical treatments by writers whose results concerning the width of the band which was required confirmed those arrived at by Carson, and whose conclusions, when any were expressed, were uniformly adverse to frequency modulation.

In 1929, Roder[3] confirmed the results of Carson and commented adversely on the use of frequency modulation.

In 1930, van der Pol[4] treated the subject and reduced his results to an excellent form for use by the engineer. He drew no conclusions regarding the utility of the method.

In 1931, in a mathematical treatment of amplitude, phase, and frequency modulation, taking into account the practical aspect of the increase of efficiency at the transmitter which is possible when the frequency is modulated, Roder[5] concluded that the advantages gained over amplitude modulation at that point were lost in the receiver.

In 1932, Andrew[6] compared the effectiveness of receivers for frequency-modulated signals with amplitude-modulated ones and arrived at the conclusion that, with the tuned-circuit method of translating the variations in frequency into amplitude variations, the frequency-modulated signals produced less than one-tenth the power of one which was amplitude modulated.

While the consensus based on academic treatment of the problem is thus heavily against the use of frequency modulation, it is to the field of practical application that one must go to realize the full extent of the difficulties peculiar to this type of signaling.

PROBLEMS INVOLVED

The conditions which must be fulfilled to place a frequency-modulated system upon a comparative basis with an amplitude-modulated one are the following:

1. It is essential that the frequency deviation shall be about a fixed point. That is, during modulation there shall be a symmetrical change in frequency with respect to this point and, over periods, there shall be no drift from it.
2. The frequency deviation of the transmitted wave should be independent of the frequency of the modulating current and directly proportional to the amplitude of that current.
3. The receiving system must have such characteristics that it responds only to changes in frequency and that for the maximum change of frequency at the transmitter (full modulation), the selective characteristic of the system responsive to frequency changes shall be such that substantially complete modulation of the current therein will be produced.
4. The amplitude of the rectified or detected current should be directly proportional to the change in frequency of the transmitted wave and independent of the rate of change thereof.
5. All the foregoing operations should be carried out by the use of aperiodic means.

THE TRANSMITTING SYSTEM

An extensive experience with the known methods of modulating the frequency convinced the writer as indeed it would anyone who had tried to work with this method of modulation at a high frequency, that some new system must be evolved. During the course of this work, there was evolved a method which, it is believed, is a complete solution to the transmitter problem. It consists in employing the modulating current to shift the phase of a current derived from a source of fixed phase and frequency, by an amount which is directly proportional to the amplitude of the of the modulating current and inversely proportional to its frequency. The resulting phase shift is then put through a sufficient number of frequency multiplications to insure 100 per cent modulation for the highest frequency of the modulating current. By keeping the initial phase shift below thirty degrees substantial linearity can be obtained.

The means employed to produce the phase shift consisted of a source of fixed frequency, a balanced modulator excited by this source, and arrangements for selecting the side frequencies from the modulator output and combining them in the proper phase with an unmodulated current derived from the initial source. The phase relations which must exist where the combination of the modulated and unmodulated currents takes place are that at the moment the upper- and lower-side frequencies produced by the balanced modulator are in phase with each other, the phase of the current of the master-oscillator frequency with which they are combined shall differ therefrom by ninety degrees.

The schematic and diagrammatic arrangements of the circuits may be visualized by reference to Figs. 1 and 2, and their operation understood from the following explanation.

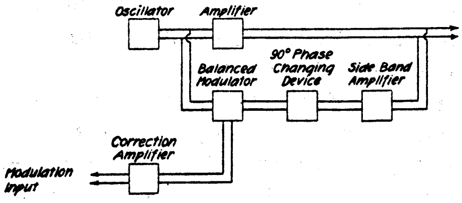

Oscillator
Amplifier
TO Multipliers
90° Phase
Balanced Modulator
Changing Device
Side Band Amplifier
Correction Amplifier
Modulation Input

Fig. 1

The master oscillator shown in these diagrams may be of the order of fifty to one-hundred thousand or more cycles per second, depending on the frequency of the modulating current.

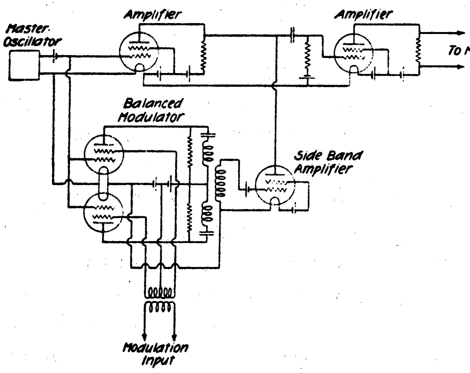

Master Oscillator
Amplifier
Amplifier
To Multipliers
Balanced Modulator
Side Band Amplifier
Modulation Input

Fig. 2

An electromotive force derived from this oscillator is applied in like phase to the grid of an amplifier and both grids of a balanced modulator. The plate circuits of the modulator tubes are made nonreactive for the frequency applied to their grids by balancing out the reactances of the transformer primaries as shown. The plate currents are, therefore, in phase with the electromotive force applied to the grid. The succeeding amplifier is coupled to the output transformer by a coil whose period is high compared to the frequency of the master oscillator, and the electromotive force applied to the grid of this amplifier when the modulator tubes are unbalanced by a modulating voltage applied to the screen grids is, therefore, shifted in phase ninety degrees (or 270 degrees) with respect to the phase of the electromotive force applied to the grids of the balanced modulators. Hence, it follows that the phase of the currents existing in the plate circuit of the amplifier of the output of the balanced modulator (at the peak of the modulation voltage) is either ninety degrees or 270 degrees apart from the phase of the current existing in the plate circuit of the amplifier of the unmodulated master-oscillator current. Therefore the voltages which they develop across the common resistance load will be ninety degrees apart.

The resulting effect on the phase of the voltage developed across the resistance in the plate circuits of these two amplifiers when modulation is applied, compared to the phase of the voltage which would exist there in the absence of modulation, will appear from Fig. 3.

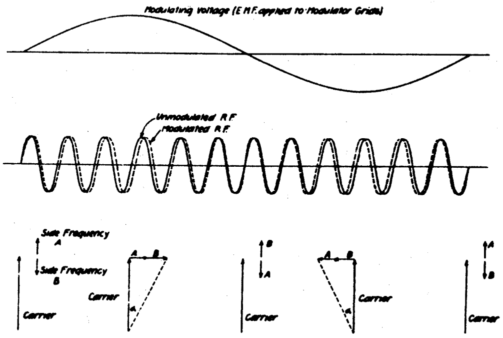

Modulating Voltage (E.M.F. applied to Modulator Grids)
Unmodulated R.F.
Modulated R.F.
Side Frequency A
Side Frequency B
Carrier
A
B
Carrier
B
A
Carrier
A
B
Carrier
A
B
Carrier

Fig. 3

It will be observed from the vector diagrams that the phase of the voltage across the common resistance load is alternately advanced and retarded by the combination of the modulated and unmodulated components, and that the maximum phase shift is given by an angle whose tangent is the sum of the peak values of the two side-frequencies divided by the peak value of the unmodulated component. By keeping this angle sufficiently small (not greater than thirty degrees), it may be made substantially proportional to the amplitude of the two side-frequencies and hence to the amplitude of the initial modulating current. It will be observed that, if the angle through which the phase is shifted be the same for all frequencies of modulation, then the rate of increase or decrease of the angle will be proportional to the frequency of modulation and, hence, the deviation in frequency of the transmitted wave will be proportional to the frequency of the modulating current.[7]

In order to insure a frequency deviation which is independent of the modulation frequency, it is necessary that, for a constant-impressed modulating electromotive force, the angle through which the phase is shifted be made inversely proportional to the frequency of the modulating current. This is accomplished by making the amplification of the input amplifier inversely proportional to the frequency by means of the correction network shown in Fig. 4.

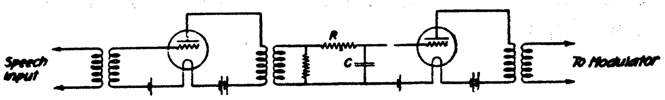


Fig. 4

The network consists of a high resistance in series with a capacity whose impedance for the lowest frequency of modulation is relatively small with respect to the series resistance. The voltage developed across the capacity which excites the succeeding amplifier stage is, therefore, inversely proportional to frequency and hence it follows that the angle through which the current is advanced or retarded becomes directly proportional to the amplitude of the modulating current and inversely proportional to its frequency. The resulting phase shift must be multiplied a great many times before a frequency-modulated current which can be usefully employed, is produced. This will be clear from an examination of the requirements of a circuit over which it is desired to transmit a frequency range from thirty to 10,000 cycles. Since the lowest frequency is limited to a phase shift of thirty degrees, it follows that for 10,000 cycles the phase shift will be but 0.09 degree. The minimum phase shift for 100 per cent modulation of the transmitted wave is forty-five degrees. A frequency multiplication of 500 times is required, therefore, to produce a wave that is fully modulated[8] and capable of being effectively handled by the receiver in the presence of disturbing currents.

Under ordinary conditions this multiplication of frequency can be realized without loss of linearity by a series of doublers and triplers operated at saturation provided the correct linkage circuits between the tubes are employed. Where, however, the wide band frequency swing which will be described subsequently in this paper is employed, unexpected difficulties arise. These also will be dealt with subsequently.

From the foregoing description it will be seen that this method of obtaining frequency modulation consists in producing, initially, phase modulation in which the phase shift is inversely proportional to the frequency of modulation, and converting the phase-modulated current into a frequency-modulated one by successive multiplications of the phase shift. The frequency stability, of course, is the stability attainable by a crystal-controlled oscillator, and the symmetry of the deviation may be made substantially perfect by compensating such asymmetrical action in the system as may occur. With the method of phase shifting shown in Fig. 2, there is an asymmetry which is of importance when the frequency of modulation is high compared to the master-oscillator frequency. It occurs in the plate transformer of the balanced modulator. The plate circuits of these tubes are substantially aperiodic and, consequently, the amplitudes of the upper- and lower-side frequencies are approximately equal and, from this, it follows that the electromotive forces induced in the secondary are directly proportional to the values of those frequencies. Where the master oscillator frequency is 50,000 cycles and a frequency of modulation of 10,000 cycles is applied, the upper-side frequency may be fifty per cent greater than the lower. This inequality may be compensated by a resistance-capacity network introduced subsequent to the point at which the combination of carrier and side frequencies is effected but prior to any point at which loss of linearity of amplitude occurs. The level in the amplifiers ahead of the compensating network must be kept sufficiently low so that the operation of the system is linear. After the side frequencies are equalized, amplitude linearity ceases to be of importance.

The performance of transmitters operating on this principle has been in complete accord with expectations. While the arrangements may seem complex and require a large amount of apparatus, the complexity is merely that of design, not of operation. The complete arrangement, up to the last few multiplier stages, may be carried out most effectively with receiving-type tubes, these last multiplier stages consisting of power-type pentodes for raising the level to that necessary to excite the usual power amplifiers.

THE RECEIVING SYSTEM

The most difficult operation in the receiving system is the translation of the changes in the frequency of the received signal into a current which is a reproduction of the original modulating current. This is particularly true in the case of the transmission of high-fidelity broadcasting. It is, of course, essential that the translation be made linearly to prevent the generation of harmonics, but it must also be accomplished in such a manner that the signaling current is not placed at a disadvantage with respect to the various types of disturbances to which radio reception is subject. In the particular type of translation developed for this purpose which employs the method of causing the changes in frequency to effect changes in amplitude which are then rectified by linear detectors, it is essential that, for the maximum deviation of the transmitted frequency, there shall be a substantial amplitude modulation of the received wave. At first sight it might appear that 100 per cent or complete modulation would be the ideal, but there are objections to approaching this limit too closely. It will however be clear that, where the translation is such that only a few percent amplitude modulation results from the maximum deviation of the frequency of the transmitted wave, the receiver is hopelessly handicapped with respect to amplitude disturbances.

This is true because, even when the level of the voltage applied to the conversion system is kept constant by a current limiting device or automatic volume control, there still remains those intervals wherein the incoming disturbances arrive in the proper phase to neutralize the signaling current in the detector, effecting thereby substantially complete modulation of the rectified current or the intervals wherein the disturbing currents themselves effect greater amplitude changes than the signal itself by cross modulation of the frequency.

An arrangement in which linear conversion can be effected without handicapping the system with respect to amplitude disturbances is illustrated diagrammatically in Fig. 5. Two branch circuits each containing resistance, capacity and inductances in series, as shown, are connected to the intermediate-frequency amplifier of a superheterodyne at some suitable frequency. One capacity and inductance combination is made nonreactive for one extreme of the frequency band which the signal current traverses, and the other capacity and inductance combination is made noninductive for the other end of the band. The resistances are chosen sufficiently high to maintain the current constant over the frequency range of the band; in fact, sufficiently high to make each branch substantially aperiodic. The reactance characteristics taken across each capacity and inductance combination will be illustrated in Fig. 6 by curves *A* and *B*.

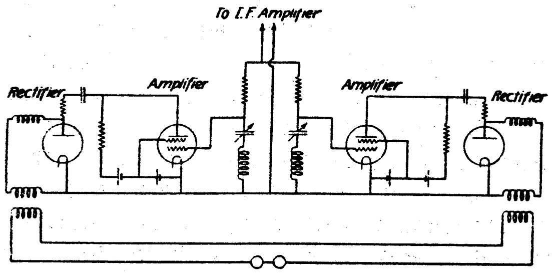


Fig. 5

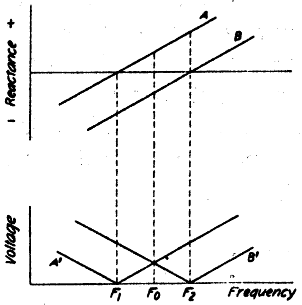


Fig. 6

Since the resistance in series with the reactance combinations are sufficient to keep the current constant throughout the frequency band, it follows that the voltages developed across each of the two combinations will be proportional to their reactances as is illustrated in curves *A'* and *B'*. The two voltages are applied respectively to the two equal aperiodic amplifiers, each of which is connected to a linear rectifier. The rectifiers are in series with equal output transformers whose secondaries are so poled that changes in the rectifier currents resulting from a change in the frequency of the received signal produce additive electromotive forces in their secondaries.

Since amplifiers and rectifiers are linear, the output currents will follow the amplitude variations created by the action of the capacity-inductance combinations. While the variation in reactance is not linear with respect to the change of frequency, particularly where the width of the band is a substantial percentage of the frequency at which the operation takes place, as a practical matter, by the proper choice of values together with shunts of high resistance or reactance, these characteristics may be rendered sufficiently straight within the working range to meet the severest requirements of high-fidelity broadcasting.

The operation of the system is aperiodic and capable of effecting 100 per cent modulation if desired, this last depending on the separation of the two nonreactive points with respect to the frequency swing. Generally, the setting of the noninductive frequency points should be somewhat beyond the range through which the frequency is swung.

There is shown in Fig. 7 an alternative arrangement of deriving the signal from the changes in frequency of the received wave, which has certain advantages of symmetry over the method just described. In this arrangement, a single capacity-inductance combination with the nonreactive point in the center of the frequency band is used, and the rectifiers are polarized by a current of constant amplitude derived from the received current. In this way, by proper phasing the polarizing current, which is in effect a synchronous heterodyne, differential rectifying action can be obtained.

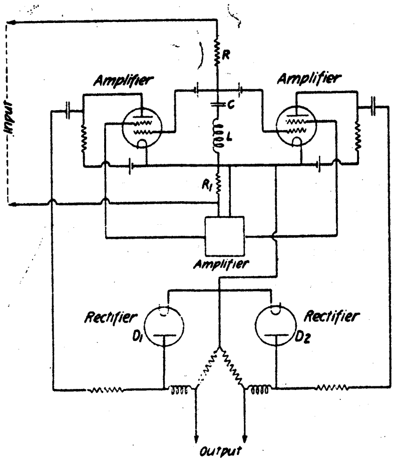


Fig. 7

In Fig. 7, the amplified output of the receiver is applied across the single series circuit consisting of resistance R, capacity C, and inductance L. The reactance of C and L are equal for the mid-frequency point of the band and the reactance curve is as illustrated in A of Fig. 8.

At frequencies above the nonreactive point the combination acts as an inductance; at frequencies below the nonreactive point, as a capacity; and the phase of the voltage developed across the combination with respect to the current through it differs, therefore, by 180 degrees above and below the nonreactive point.

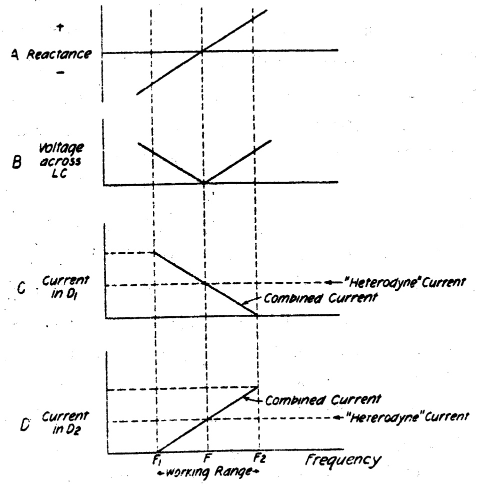


Fig. 8

Since the current through the circuit in maintained constant over the working range by the resistance R and since the resistance of the capacity C and inductance L may be made very low, the electromotive force developed across C and L is of the form shown in curve B. This curve likewise represents the variation in voltage with variation in frequency which is applied to the grids of the amplifiers and eventually to the two rectifiers D_1 and D_2.

The heterodyning or polarizing voltage is obtained by taking the drop across resistance R_1, amplifying it, changing its phase through ninety degrees and applying the amplified voltage to the screen grids of the amplifiers in opposite phase. The characteristic of this amplifying and phase changing system must be flat over the working range. Under these conditions the signaling and heterodyning voltages are exactly in phase in one rectifier and 180 degrees out of phase in the other, and hence for a variable signaling frequency the rectifying characteristics are as shown in curves C and D, the detector outputs being cumulatively combined for voltage changes. Adjustment of the relative amplitudes of the signaling and polarizing voltages in the rectifier controls the degree of amplitude modulation produced from 100 per cent down to any desired value.

PART II

With the foregoing description of the instrumentalities for transmitting and receiving modulated waves, it is now in order to consider the main object of the paper: the method of reducing disturbances and the practical results obtained by its use.

METHOD OF REDUCING DISTURBANCES

The basis of the method consists in introducing into the transmitted wave a characteristic which cannot be reproduced in disturbances of natural origin, and utilizing a receiving means which is substantially not responsive to the currents resulting from the ordinary types of disturbances and fully responsive only to the type of wave which has the special characteristic.

The method to be described utilizes a new principle in radio signaling, the application of which furnishes an interesting conflict with one which has been a guide in the art for many years; i.e., the belief that the narrower the band of transmission, the better the signal-to-noise ratio. That principle is not of general application. In the present method an opposite rule applies.

It appears that the origin of the belief that the energy of the disturbance created in a receiving system by random interference depended on the band width goes back almost to the beginning of radio. In the days of spark telegraphy, it was observed that "loose coupling" of the conventional transmitter and receiver circuits produced a "sharper wave" and that interference from lightning discharges, the principle "static" of those days of insensitivity and nonamplifying receivers, was decreased. Further reduction in interference of this sort occurred when continuous-wave transmitters displaced the spark and when regeneration narrowed the band width of the receiving system. It was observed, however, that "excessive resonance" must not be employed either in telegraphic or, more particularly, in telephonic signaling or the keying and speech would become distorted. It was concluded in a quantitative way that there was a certain "selectivity" which gave the best results.

In 1925, the matter was placed on a quantitative basis by Carson [9] where, in a mathematical treatment of the behavior of selective circuits when subjected to irregular and random interference (with particular reference to "static") on the basis of certain assumptions, the proposition was established that "if the signaling system requires the transmission of the band of frequencies corresponding to the interval $w_2 - w_1$ and, if the selective circuit is efficiently designed to this end, then the mean square interference current is proportional to the frequency band width $(w_2 - w_1)/2$.

Hazeltine[10] pointed out that when a detector was added to such a system and a carrier of greater level than the interference currents was present, that for aural reception, only those components of the interfering current lying within the audible range of the carrier frequency were of importance, and that Carson's theory should be supplemented by the use of a factor equal to the relative sensitivity of the ear at different frequencies.With the discovery of shot-effect and thermal-agitation noises and the study of their effect on the limit of amplification quantitative relations akin to those enunciated by Carson with respect to static were found to exist.

Johnson,[11] reporting the discovery of the electromotive force due to thermal agitation and considering the problem of reducing the noise in amplifiers caused thereby, points out that for this type of disturbance the theory indicates, as in the Carson theory, that the frequency range of the system should be made no greater than is essential for the proper transmission of the applied input voltage, that where a voltage of constant frequency and amplitude is used, one may go to extremes in making the system selective and thereby proportionately reducing the noise, but that when the applied voltage varies in frequency or amplitude the system must have a frequency range which takes care of these variations and the presence of a certain amount of noise must be accepted.

Ballantine[12] in a classical paper discussing the random interference created in radio receivers by shot and thermal effects obtained a complete expression for the noise output.[13]

Johnson and Llewellyn,[14] in a paper dealing generally with the limits of amplification, point out that in a properly-designed amplifier, the limit resides in thermal agitation in the input circuit to the amplifier, that the power of the disturbance in the output of the amplifier is proportional to its frequency range and that this, the only controllable factor in the noise equation, should be no greater than is needed for the transmission of the signal. A similar conclusion is reached in the case of a detector connected to the output of a radio-frequency amplifier and supplied with a signal carrier.

It is now of interest to consider what happens in a linear detector connected to the output of a wide band amplifier which amplifies uniformly the range from 300 to 500 kilocycles. Assume that the amplification be sufficiently great to raise the voltage due to thermal agitation and shot effect to a point sufficient to produce straight-line rectification and that no signal is being received. Under these conditions, the frequencies from all parts of the spectrum between 300 and 500 kilocycles beat together to contribute in the output of the detector to the rough hissing tone with which the art is familiar. The spectrum of frequencies in the rectified output runs from some very low value which is due to adjacent components throughout the range beating with one another to the high value of 200 kilocycles caused by the interference of the extremes of the band.

It is important to note that all parts of the 300 to 500 kilocycle spectrum contribute to the production of the detector output of those frequencies with which we are particularly interested - those lying within the audible range.

Assume now that an unmodulated signal carrier is received of, for example, 400 kilocycles and that its amplitude is greater than that of the disturbing currents. Under these circumstances an entirely new set of conditions arise. The presence of the 400 kilocycle current stops the rectification of the beats which occur between the various components of the spectrum within the 300- to 500-kilocycle band and forces all rectification to take place in conjunction with the 400-kilocycle carrier. Hence, in the output of the rectifier there is produced a series of frequencies running from some low value up to 100 kilocycles. The lowest frequency is produced by those components of the spectrum which lie adjacent to the 400-kilocycle current, the highest by those frequencies which lie at the extremity of the band; i.e., 300 and 500 kilocycles, respectively.

The characteristics of the rectifiers and the magnitude of some of the effects involved in the above-described action may be visualized by reference to the succeeding figures. The actual demodulation of the beats occurring between adjacent-frequency components by the presence of the 400-kilocycle current is shown by the characteristic of Fig. 9, which illustrates what happens to the output voltage of a rectifier produced by beating together two equal currents of 350 and 351 kilocycles, respectively, when a 400-kilocycle current is introduced in the same rectifier and its amplitude progressively increased with respect to the amplitude of these two currents.

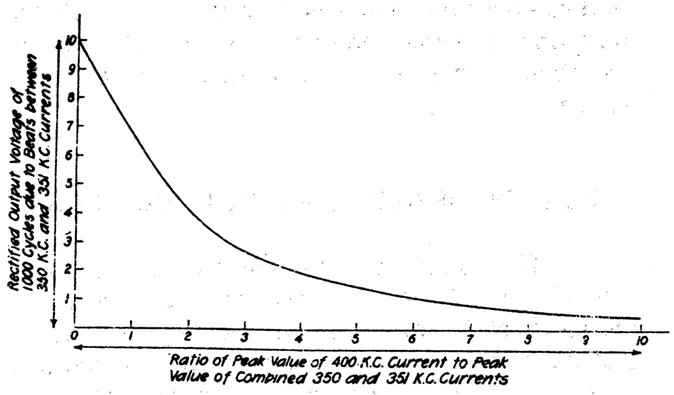


Fig. 9

The characteristic was obtained with the arrangement shown in Fig. 10, in which two oscillators of 350 and 351 kilocycles produced currents of equal strength in a linear rectifier, this rectifier consisting of a diode in series with 10,000 ohms resistance. The output of the rectifier is put through a low-pass filter, a voltage divider, and an amplifier. The 400-kilocycle current is introduced into the rectifier without disturbing the voltage relations of the other two oscillators and the effect on the rectified output voltage observed as the 400 kilocycle is increased. The purpose of the low-pass filter is to prevent the indicating instrument from responding to the 49- or 50-kilocycle currents produced by the interaction of the 350- and 351-kilocycle currents with the current of 400 kilocycles.

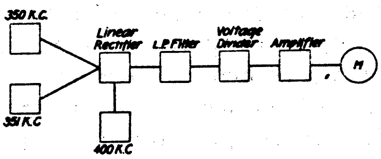


Fig. 10

The linearity characteristic of the rectifier is shown in Fig. 11 where the voltage produced by the beats between a current of constant amplitude, and one whose amplitude is raised from equality with to many times the value of the first current, is plotted against the ratio of the two.

The linearity of the rectifier is such that after the ratio of the current becomes two-to-one, no further increase in rectifier-output voltage results. In fact with the levels used in these measurements when the two currents are equal, there is an efficiency of rectification of only about twenty per cent less than the maximum obtained.

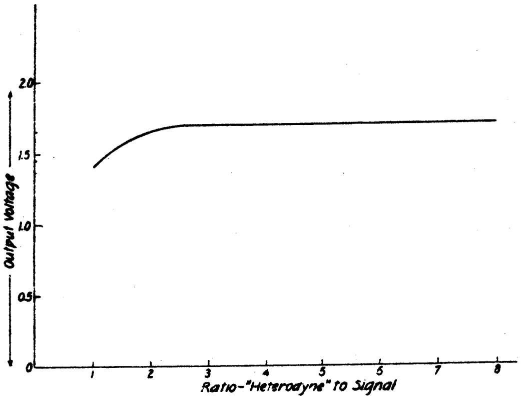


Fig. 11

It is important to note here that the only frequencies in the spectrum which contribute to the production of currents of audible frequency in the detector output circuit are those lying within audible range of the signal carrier. We may assume this range as roughly from 390 to 410 kilocycles. The frequencies lying beyond these limits beat against the 400-kilocycle carrier and, of course, are rectified by the detector but the rectified currents which are produced are of frequencies which lie beyond the audible range and produce, therefore, no effect which is apparent to the ear. It follows that, if the signal carrier is somewhat greater in amplitude than the disturbing currents, the signal-to-noise ratio for a receiver whose band of admittance covers twice the audible range will be the same as for one whose band width is many times that value. (There are, of course, certain second-order effects but they are of such minor importance that the ear cannot detect them). The amplitude of the disturbances in the detector output will vary in accordance as the components of the disturbing currents come into or out of phase with the signal carrier, the rectified- or detector-output current increasing above and decreasing below the level of the rectified carrier current by an amount proportional to the amplitude of the components of the 300 - 500 kilocycle band. The reasons for the independence of the signal-to-noise ratio of the band-width under the circumstances which have been described should now be apparent. In any event, it can be readily demonstrated experimentally.

It is now in order to consider what happens when a current-limiting device is introduced between the output of the amplifier and the detector input. (Assume signal level still above peak-noise level.) Two effects will occur. One of the effects will be to suppress in the output circuit of the limiter, all components of the disturbing currents which are in phase with, or opposite in phase to, the 400-kilocycle carrier. The other effect will be to permit the passage of all components of the disturbing currents which are in quadrature with the 400-kilocycle current.

Both the above effects are brought about by a curious process which takes place in the limiter. Each component within the band creates an image lying on the opposite side of the 400-kilocycle point whose frequency difference from the 400-kilocycle current is equal to the frequency difference between that current and the original component. The relative phase of the original current in question, the 400-kilocycle current and the image current, is that of phase modulation -- that is, at the instant when the original component and its image are in phase with each other, the 400-kilocycle current will be in quadrature with them both and, at the instant that the 400-kilocycle current is in phase with one of these two frequencies, it will be out of phase with the other.

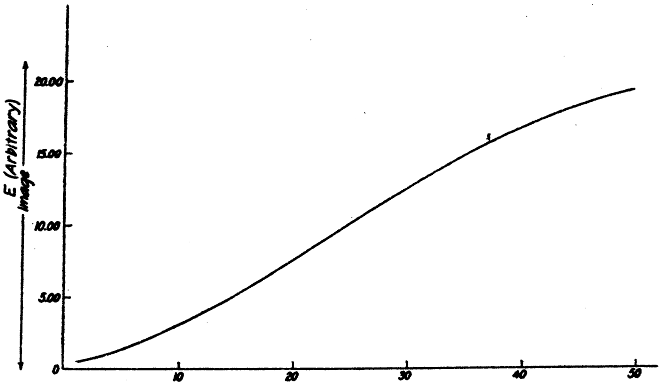


Fig. 12

The relation (obtained experimentally) between the amplitudes of the original current and the image is illustrated by the curve of Fig. 12, which shows the relation between the amplitude of a 390-kilocycle current introduced into a limiter along with the 400-kilocycle current, and the resulting 410-kilocycle image in terms of percentage amplitude of the 400- kilocycle current.

It will be obvious from the curve that in the region which is of interest - that is, where the side frequencies are smaller than the mid-frequency - that the effect is substantially linear.

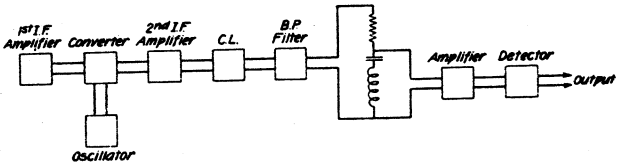


Fig. 13

With the above understanding of what takes place in the current limiter, it is now in order to consider what happens when a selective system as illustrated in Fig. 13 is interposed between the limiter and the detector. (The band-pass filter is for the purpose of removing limiter harmonics.) A rough picture of what occurs may be had by considering a single component of the interference spectrum. Suppose this component to be at 390 kilocycles and that, by the action already explained, it has created its image at 410 kilocycles. These two frequencies are equal in amplitude and so phased with respect to each other and with respect to the 400-kilocycle carrier that no amplitude change results.

Assume now that the selective system has the characteristic which, as shown in Fig. 14, is designed to give complete modulation for a ten-kilocycle deviation of frequency.

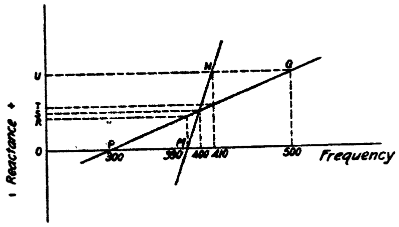


Fig. 14

Since at 390 kilocycles the reactance across the capacity-inductance combination is zero and, at 410 kilocycles, double what it is at 400 kilocycles, it follows that the 390-kilocycle component becomes equal to zero but the ratio of the 410-kilocycle component to the 400-kilocycle carrier is doubled; that is, it is twice as great as is the ratio in the circuits preceding the selective system. The change in amplitude, therefore, becomes proportional to *OU*. Therefore, in combination with the 400-kilocycle carrier, a variation in amplitude is produced which is substantially identical with that which would be obtained were the current limiter removed and the selective system replaced by an aperiodic coupling of such value that the same detector level were preserved.

Now consider what occurs when a selective system having the characteristic such as *PQ* and requiring a deviation of 100 kilocycles to produce full modulation is employed instead of one such as *MN*, where a ten-kilocycle deviation only is required. Assume the same conditions of interference as before. The 400-kilocycle voltage applied to the rectifier will be the same as before, but the *relative amplitudes of the 390- and 410-kilocycle voltages will only be slightly changed*. The 410-kilocycle voltage will be increased from a value which is proportional to *OS* to one which is proportional to *OT* and the 390-kilocycle voltage will be reduced from a value proportional to *OS* to one proportional to *OR*. The difference in value of the two frequencies will be proportional to the difference between *OS* and *OT* or *RT*, and the change in amplitude produced by their interaction with the 400-kilocycle current will be likewise proportional to *RT*. The reduction in the amplitude of the disturbance, as measured in the detector output by the use of a 200-kilocycle wide selective system as compared to the use of one only twenty-kilocycles wide, is therefore the ratio *RT/OU*. In this case, it is ten percent. The power ratio is the square of this, or one percent.

The above reasoning holds equally well if a balanced rectifying system is used where the characteristics of the selective system are as shown in Fig. 15.

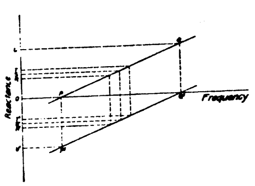


Fig. 15

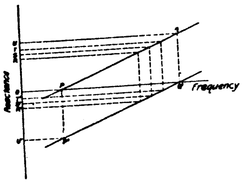


Fig. 16

The output of the system insofar as voltages resulting from changes in frequency are concerned is the sum of outputs of the two sides of the balance. It is, of course, clear that disturbing currents lying farther from the 400-kilocycle point than the ten-kilocycle limit will, by interaction with the 400-kilocycle current, produce larger values of rectified current than those lying within that band. *But the rectified currents produced in the detector output by those components of frequency which lie at a greater than audible frequency distance from the 400-kilocycle current will be beyond the audible range and hence will produce no disturbance which is audible.* (It is generally advisable to eliminate them from the audio amplifier by a low-pass filter to prevent some incidental rectification in the amplifier making their variations in amplitude audible.)

It remains only to consider what happens when the frequency of the 400-kilocycle current is varied in accordance with modulation at the transmitter. It is clear from Fig. 14 that when the selective system has the characteristic *MN,* that a deviation of 10,000 cycles will produce complete modulation of the signal or a change in amplitude proportional to *OU.* Similarly, when the characteristic is according to the curve *PQ,* it is clear that a 100,000-cycle deviation is required to produce complete modulation which is, likewise, proportional to the same value *OU.* As the signal current is swung back and forth over the range of frequencies between 300 and 500 kilocycles, the band of frequencies from which the audible interference is derived continually changes: the band progressively lying about ten-kilocycles above and ten-kilocycles below what we may call the instantaneous value of the frequency of the signal. The effect is illustrated by Fig. 16 and from this, it will be seen that the amplitude of the disturbances in the output circuit of the rectifiers, which is proportional to the sum of *RT* and *R'T',* will be constant. This will be true where the ratio of the amplitude of the signal to the disturbing currents is sufficiently large; where this condition does not exist, then there are certain other effects which modify the results, but these effects will only be of importance at the limits of the practical working range.

COMPARISON OF NOISE RATIOS OF AMPLITUDE AND FREQUENCY MODULATION SYSTEMS

From the foregoing description, it will be clear that as between two frequency-modulation systems of different bandwidths, the signal-to-noise power ratio in the rectified output will vary directly as the square of the bandwidth (provided the noise voltage at the current limiter is less than the signaling voltage). Thus doubling the bandwidth produces an improvement of 4 to 1 and increasing it tenfold, an improvement of 100 to 1.

The comparison of relative noise ratios of amplitude- and frequency-modulation systems cannot be made on so simple a basis as there are a number of new factors which enter, particularly when the comparison is viewed from the very practical aspect of how much greater power must be used with an amplitude-modulated transmitter than with a frequency-modulated one. If the academic comparison be made between a frequency-modulated system having a deviation of ten kilocycles and an amplitude-modulated one of similar bandwidth and the same carrier level (also same fidelity), it will be found that the signal-to-noise voltage ratio as measured by a root-mean-square meter will favor the frequency-modulation system by about 1.7 to 1, and that the corresponding power ratio will be about 3 to 1. This improvement is due to the fact that, in the frequency-modulation receiver, it is only those noise components which lie at the extremes of the band; viz., ten kilocycles away from the carrier which, by interaction with the carrier (when unmodulated), can produce the same amplitude of rectified current as will be produced by the corresponding noise component in the amplitude-modulated receiver.

Those components which lie closer to the carrier than ten kilocycles will produce a smaller rectified voltage, the value of this depending on their relative distance from the carrier. Hence the distribution of energy in the rectified current will not be uniform with respect to frequency but will increase from zero, at zero frequency, up to a maximum at the limit of the width of the receiver, which is ten kilocycles in the present case. The root-mean-square value of the voltage under such a distribution is approximately 0.6 of the value produced with the uniform distribution of the amplitude receiver.

Similarly, in comparing an amplitude-modulating system arranged to receive ten-kilocycle modulation and having, of course, a bandwidth of twenty kilocycles with a 100-kilocycle deviation frequency-modulation system (same carrier level and fidelity), there will be an improvement in noise voltage ratio of:

$$1.7 \times \frac{\text{deviation}}{\text{audio-frequency range}} \quad \text{or} \quad 1.7 \times \frac{100}{10} = 17$$

The above comparisons have been made on the basis of equal carrier. The practical basis of comparison between the two is that of half-carrier for the amplitude-modulation and full-carrier for the frequency-modulation system. This results in about the equivalent amount of power being drawn from the mains by the two systems. On this basis, the voltage improvement becomes thirty-four and the signal-to-noise power ratio to 1156. Where the signal level is sufficiently large with respect to the noise, it has been found possible to realize improvements of this order.

The relative output signal-to-noise ratios of an amplitude-modulation system fifteen-kilocycles wide (7.5-kilocycle modulation frequency) and a frequency-modulation system 150-kilocycles wide (75-kilocycle deviation) operating on forty-one megacycles, have been compared on the basis of equal fidelity, and half-carrier for amplitude modulation. The characteristic of the selective system for converting frequency changes to amplitude changes, which was used, is shown in Fig. 17.

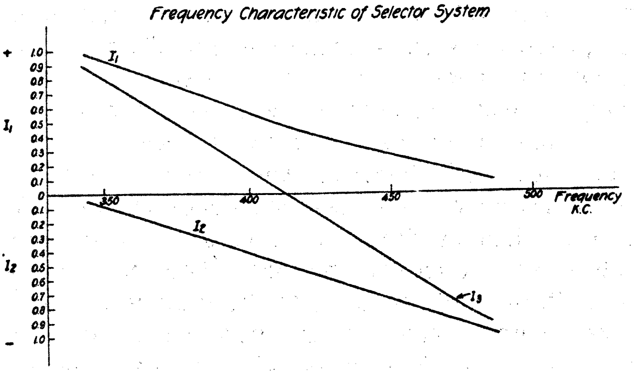


Fig. 17

The variation of the output signal-to-noise ratio with respect to corresponding radio-frequency voltage ratio is illustrated in Fig. 18.

The curves show that, where the radio-frequency peak-voltage of the noise measured at the current limiter is less than ten per cent of the signal peak-voltage, then the energy of the disturbance in the rectified output will be reduced by a factor which is approximately 1100 to 1.

When the peak radio-frequency-noise voltage is twenty-five percent of the signal peak-voltage, then the energy of the disturbance in the rectified output has been reduced to about 700 to 1, and when it is fifty percent, the reduction of the disturbance drops below 500 to 1. Finally, when the noise and signal peak-voltages become substantially equal, the improvement drops to some very low value. While it is unfortunate, of course, that the nature of the effect is such that the amount of noise reduction becomes less as the noise level rises with respect to the signal, nevertheless this failing is not nearly so important as it would appear.

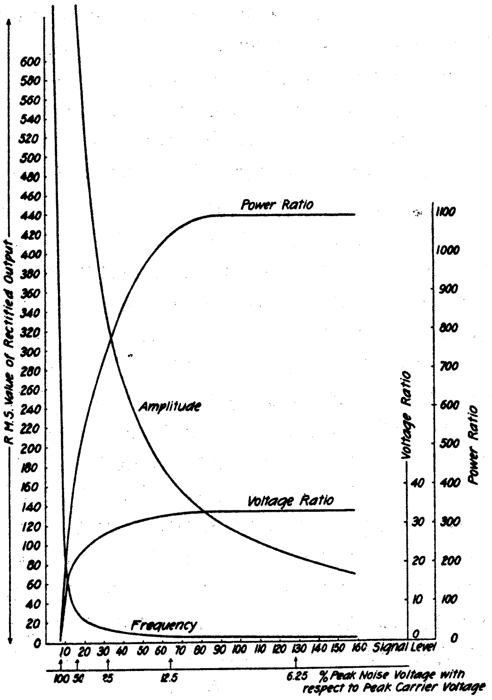


Fig. 18

In the field of high-fidelity broadcasting, a signal-to-noise voltage ratio of at least 100 to 1 is required for satisfactory reception. It is just within those ranges of noise ratios which can be reduced to this low level that the system is most effective. The arrangements employed in obtaining these characteristics and the precaution which must be observed may perhaps be of interest. As it was obviously impracticable to vary the power of a transmitter over the ranges required or to eliminate the fading factor except over short periods of time, an expedient was adopted. This expedient consisted in tuning the receiver to the carrier of a distant station, determining levels and then substituting for the distant station a local signal generator, the distant station remaining shut down except as it was called upon to check specific points on the curve. Observations were taken only when noise was due solely to thermal agitation and shot effect.

Fig. 19 shows the arrangement of apparatus. The receiver was a two-intermediate-frequency super-heterodyne with provision for using either a narrow-band second-intermediate-amplifier with the amplitude-modulation system or a wide-band amplifier with the frequency-modulation system. The band width of the amplitude-modulation system was fifteen kilocycles or twice the modulation- frequency range. The band width of the frequency- modulation receiver was 150 kilocycles or twice the frequency deviation.

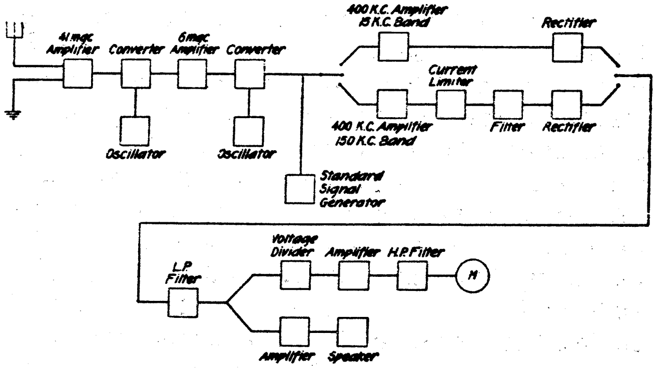


Fig. 19

Provision was made for shifting from one intermediate amplifier to the other without disturbing the remainder of the system. The forty-one-megacycle circuits and the first intermediate-amplifier circuits were wide enough to pass the frequency swing of 150 kilocycles. Identical detection circuits were used, the frequency-modulation detector being preceded by a selective system for translating changes in frequency into changes in amplitude. The output circuits of the detectors were arranged to connect alternately to a 7500-cycle low-pass filter with a voltage divider across its output. An amplifier with a flat characteristic over the audible range and a root-mean-square meter connected through a high-pass, 500-cycle filter provided the visual indication.

The standard signal was introduced into the input of the two branches of the intermediate-frequency stage at 400 kilocycles. As long as the receiver is linear between the antenna and the point at which the standard signal is introduced, it is immaterial whether the signal be of forty-one megacycles, six megacycles, or 400 kilocycles. This has been checked experimentally, but 400 kilocycles was chosen on account of the greater accuracy of the signal generator on low frequencies.

The relative noise levels to be compared varied over such ranges that lack of linearity had to be guarded against and readings were made by bringing the output meter to the same point on the scale each time by adjustment of the voltage divider, and obtaining the relative voltages directly from the divider.

Two other precautions are essential. The absolute value of the noise voltage on the frequency-modulation system becomes very low for high signal levels. If the voltages due to thermal agitation and shot effect are to be measured rather than those due to the power-supply system, the output meter must be protected by a high-pass filter of high attenuation for the frequencies produced by the power system.

The cutoff point should be kept as low as possible since because of the difference in the distribution of energy in the rectified outputs of frequency- and amplitude-modulation receivers already referred to, there is a certain error introduced by this filter which is small if the bandwidth excluded by the filter is small, but which can become appreciable if too much of the low-frequency part of the modulation range be suppressed.

A second precaution is the use of a low-pass filter to cut off frequencies above the modulation range. Because of the wide band passed by the amplifiers of the frequency-modulation part of the system, there exists in the detector output, rectified currents of frequencies up to seventy-five kilocycles. The amplitude of these higher frequencies is much greater than those lying within the audible range. The average detector output transformer will readily pass a substantial part of these superaudible frequencies which then register their effect upon the output meter although they in no way contribute to the audible disturbance.

The procedure which was followed in making the measurements we are considering consisted in tuning the receiver to the distant transmitter and adjusting the two detector levels to the same value for the respective carrier levels to be employed. This was done by cutting the carrier in half at the transmitter when the amplitude-modulation detector level was being set and using full carrier for the adjustment of the frequency-modulation detector. Each system was then modulated seventy-five percent and output voltages checked against each other. If they were equal, the modulation was removed and the relative noise voltages were measured for the respective carrier levels. This gave the first point on the curve.

The transmitter was then shut down and a local carrier introduced which gave the same level in the 400-kilocycle intermediate-amplifier circuits as the half-carrier distant signal. This level was directly ascertainable from the rectified detector-current in the amplitude-modulation system. From this point on, the procedure was entirely within the control of the receiving station. The noise ratios could be compared at any signal level by adjusting the voltage introduced by the signal generator to any fraction of that of the distant signal, bringing the level in the amplitude-modulation detector up to the same original value by adjustment of the amplification of the second intermediate-amplifier (the frequency-modulation detector stays at its point of reference because of the current limiter) and comparing the two output voltages. The level of the detector in the amplitude-modulation receiver was, of course, set with the half-carrier value of the signal generator and the output voltage measured at that level. The output voltage of the frequency-modulation system was measured when twice that voltage was applied.

It is important to keep in mind just what quantities have been measured and what the curves show. The results are a comparison between the relative noise levels in the two systems (root-mean-square values) *when they are unmodulated.* In both an amplitude- and in a frequency-modulation receiver, the noise during modulation may be greater than that obtained without modulation. In the frequency-modulation receiver, two principal sources may contribute to this increase, one of which is of importance only where the band for which the receiver is designed is narrow, the other of which is common to all band widths.

If the total band width of the receiver is twenty kilocycles and if the deviation is, for example, ten kilocycles, then as the carrier frequency swings off to one side of the band, it approaches close to the limit of the filtering system of the receiver. Since the sides of the filter are normally much steeper than the selective system employed to convert the changes in frequency into amplitude variations and since the frequency of the signaling current will have approached to within the range of good audibility of the side of the filter, a considerable increase in both audibility and amplitude of disturbance may occur, caused by the sides of the filter acting as the translating device. This effect is obviously not of importance where a wider frequency swing is employed.

The other source of noise which may occur when the signal frequency swings over the full range, is found in systems of all band widths. It was first observed on an unmodulated signal when it was noted that swinging the intermediate frequency from the mid-point to one side or the other by adjustment of the frequency of the first heterodyne produced an increase in the amplitude and a change in the character of the noise. The effect was noted on a balanced-detector system and, at first, it was attributed to the destruction of the amplitude balance as one detector current became greater than the other. Subsequently, when it was noted that the increase in the noise was produced by the detector with the smaller current and that the effect was most pronounced when the signal level was relatively low, the explanation became apparent. As long as the signal frequency was set at the mid-point of the band, its level in the detector was sufficiently large to prevent the production of audible beats between the noise components lying respectively at the two ends of the band where the reactance of the selective systems is a maximum.

When, however, the signal frequency moves over to one side of the band, the amplitude of the voltage applied to one of the detectors progressively decreases, approaching zero as the frequency coincides with the zero-reactance point of the selective system. The demodulating effect of the signaling current therefore disappears and the noise components throughout the band, particularly those at the other side of it, are therefore free to beat with each other. The noise produced is the characteristic one obtained when the high-frequency currents caused by thermal agitation and shot effect are rectified in a detector without presence of a carrier. The effect is not of any great importance on the ordinary working levels for simplex operation although it may become so in multiplex operation. It indicates, however, that where the signal-to-noise level is low, complete modulation of the received signal by the conversion system is not desirable and that an adjustment of the degree of modulation for various relative noise levels is advantageous.

In the course of a long series of comparisons between the two systems, a physiological effect of considerable importance was noted. It was observed that while a root-mean-square meter might show the same reading for two sources of noise, one derived from the amplitude-modulation, and the other from a frequency-modulation receiver (both of the same fidelity) that the disturbance perceived by the ear was more annoying on the amplitude-modulation system. The reason for this is the difference in the distribution of the noise voltage with respect to frequency in the rectified output currents of the two systems, the distribution being substantially uniform in the amplitude system but proportional to the frequency in the frequency-modulation system. Hence, in the latter, there is a marked absence of those frequencies which lie in the range to which the ear is most sensitive. With most observers, this difference results in their appraising a disturbance produced in the speaker by an amplitude-modulation system as the equivalent of one produced therein by a frequency-modulation system of about 1.5 times the root-mean-square voltage although, of course, the factor varies considerably with the individual's aural system.

On account of this difference in distribution of energy, the correct method of procedure in making the comparison is that given in the article by Ballentine [16] but lack of facilities for such determinations made necessary the use of a root-mean-square meter for the simultaneous measurement of the entire noise frequency range. The increase in noise voltage per frequency interval with the frequency may be readily demonstrated by means of the ordinary harmonic analyzer of the type now so generally used for the measurement of distortion.

Because of the extremely narrow frequency interval of these instruments, it is not possible to obtain sufficient integration to produce stable meter readings and apparatus having a wider frequency interval than the crystal-filter type of analyzer must be used. The observation of the action of one of these analyzers will furnish convincing proof that peak-voltmeter methods must not be used in comparing the rectified output currents in frequency- and amplitude-modulated receivers.

All the measurements which have been hereto-fore discussed were taken under conditions in which the disturbing currents had their origin in either thermal agitation or shot effect, as the irregularity of atmospheric disturbances or those due to automobile ignition systems were too irregular to permit reproducible results. The curves apply generally to other types of disturbances providing the disturbing voltage is not greater than that of the signal. When that occurs, a different situation exists and will be considered in detail later.

There are numerous second-order effects produced but, as they are of no great importance, consideration of them will not be undertaken in the present paper.

THE NEW YORK - WESTHAMPTON AND HADDONFIELD TESTS

The years of research required before field tests could even be considered were carried out in the Marcellus Hartley Research Laboratory at Columbia University. Of necessity, both ends of the circuit had to be under observation simultaneously, and a locally-generated signal was used. The source of the signal ultimately employed consisted of a standard signal generator based upon the principle of modulation already described and capable of giving 150,000 cycles swing on forty-four megacycles. The generator was also arranged to give amplitude-modulated signals. Suitable switching arrangements for changing rapidly from frequency to amplitude modulation at either full or half carrier were set up and a characteristic similar to that of Fig. 18 ultimately obtained.

A complete receiving system was constructed and, during the winter of 1933 - 34, a series of demonstrations were made to the executives and engineers of the Radio Corporation of America. That wholly-justified suspicion with which all demonstrations of "static eliminators" should be properly regarded was relieved when C. W. Horn of the National Broadcasting Company placed at the writer's disposal, a transmitter in that company's experimental station located on top of the Empire State Building in New York City. The transmitter used for the sight channel of the television system delivered about two kilowatts of power at forty-four megacycles to the antenna and it was the one selected for use. This offer of Mr. Horn's greatly facilitated the practical application of the system as it eliminated the necessity of transmitter construction in a difficult field and furnished the skilled assistance of R.E. Shelby and T.J. Buzalski, the active staff of the station at that time. Numerous difficulties, real and imaginary, required much careful measurement to ascertain the presence or absence and the relative importance of those actually existing. The most troublesome was due to the position of the transmitter which is located on the eighty-fifth floor of the building and is connected by a concentric transmission line approximately 275 feet long with a vertical dipole antenna about 1250 feet above ground. Investigation of the characteristics of this link between transmitter and antenna showed it to be so poorly matched to the antenna that the resulting standing waves attained very large amplitude.

The problem of termination afforded peculiar difficulties because of the severe structural requirements of the antenna above the roof and of the transmission line below it. It was, however, completely solved by P.S. Carter of the R.C.A. Communications Company in a very beautiful manner, the standing waves being practically eliminated and the antenna broadened beyond all requirements of the modulating system contemplated. With the transmitter circuits, no difficulty was encountered at this time. The frequency of the system was ordinarily controlled by a master oscillator operating at 1733 kilocycles which was multiplied by a series of doublers and triplers to forty-four megacycles. The multiplier and amplifier circuits were found to be sufficiently broad for the purposes of the initial tests.

The crystal-control oscillator was replaced by the output of the modulation system shown in Fig. 20 in which an initial frequency of 57.33 kilocycles was multiplied by a series of doublers up to the input frequency of the transmitter of 1733 kilocycles.

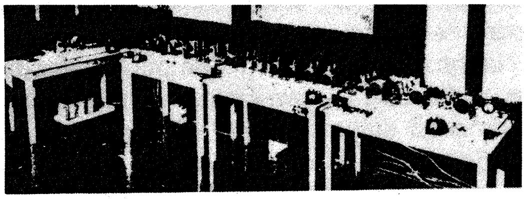


Fig. 20

It was found possible to operate this apparatus as it is shown installed in the shielded room of the television studio at the Empire State Building, as the shielding furnished ample protection against the effects of the high-power stages of the transmitter located some seventy-five feet away.

The receiving site selected was at the home of George E. Burghard, at Westhampton Beach, Long Island, one of the original pioneers of amateur radio, where a modern amateur station with all facilities including those for rigging directive antennas, were at hand. Westhampton is about sixty-five miles from New York and 800 or 900 feet below line of sight.

The installation is illustrated in Figs. 21 and 22 which show both frequency and amplitude modulation receivers and some of the measuring equipment for comparing them.

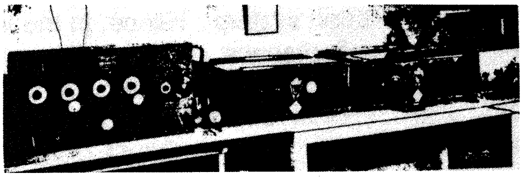


Fig. 21

The frequency-modulation receiver consisted of three stages of radio-frequency amplification (at forty-one megacycles) giving a gain of about 100. This frequency was heterodyned down to six megacycles where an amplification of about 2000 was available and this frequency was, in turn, heterodyned down to 400 kilocycles where an amplification of about 1000 could be realized. Two current-limiting systems in cascade, each with a separate amplifier, were used. At the time the photograph was taken, the first two radio-frequency stages had been discarded.

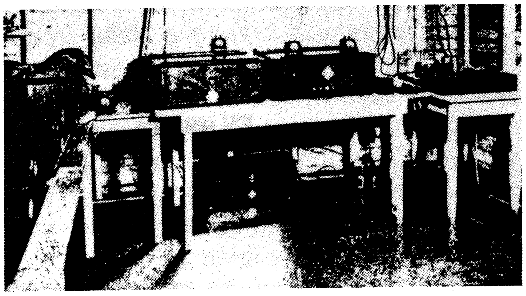


Fig. 22

The initial tests in the early part of June surpassed all expectations. Reception was perfect on any of the antennas employed; a ten-foot wire furnished sufficient pickup to eliminate all background noises. Successive reductions of power at the transmitter culminated at a level subsequently determined as approximately twenty watts. This gave a signal comparable to that received from the regular New York broadcast stations (except WEAF, a fifty-kilowatt station approximately forty miles away.)

The margin of superiority of the frequency-modulation system over amplitude modulation at fort-one megacycles was so great that it was at once obvious that comparisons of the two were principally of academic interest.

The real question of great engineering and economic importance was the comparison of the ultra-short-wave frequency-modulation system with the existing broadcast service and the determination of the question of whether the service area of the existing stations could not be more effectively covered than at present. The remainder of the month was devoted to such a comparison. With the Empire State transmitter operating with approximately two kilowatts in the antenna, at all times and under all conditions the service was superior to that provided by the existing fifty-kilowatt stations, this including station WEAF. During thunderstorms, unless lightning was striking within a few miles of Westhampton, no disturbances at all would appear on the system, while all programs on the regular broadcast system would be in a hopeless condition. Background noise due to thermal agitation and tube hiss were likewise much less than on the regular broadcast system.

The work at Westhampton demonstrated that, in comparing this method of transmission with existing methods, two classes of services and two bases of comparison must be used. It was found that the only type of disturbance of the slightest importance was caused by the ignition systems of automobiles, where the peak voltage developed by the interference was greater than the carrier level. In point-to-point communication, this difficulty can be readily guarded against by proper location of the receiving system, and then thermal agitation and shot effect are the principal sources of disturbances; lightning, unless in the immediate vicinity, rarely produces voltages in excess of the carrier level which would normally be employed to suppress the thermal and shot effects. Under these conditions, the full effect of noise suppression is realized and comparisons can be made with precision by means of the method already described in this paper.

An illustration of the practical accomplishment of this occurred at Arney's Mount, the television relay point between New York and Camden, of the Radio Corporation of America. This station is located about sixty miles from the Empire State Building and the top of the tower is only a few feet below line of sight. It is in an isolated spot and the noise level is almost entirely due to the thermal and shot effects. It was noted by C.M. Burrill of the RCA Manufacturing Company who made the observations at Arney's Mount that, with fifty watts in the antenna, frequency-modulated (produced by a pair of UX 852 tubes), a signal-to-noise ratio of the same value as the two-kilowatt amplitude-modulation transmitter (eight-kilowatt peaks) was obtained.

The power amplifier and the intermediate power amplifier of the frequency modulation transmitter is shown in Fig, 23.

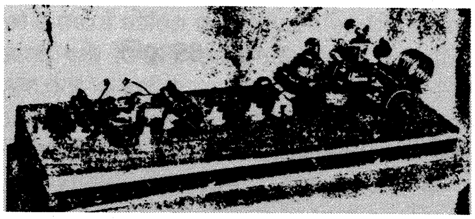


Fig. 23

The signal with fifty-watts output would undoubtedly have had a better noise ratio than the two-kilowatt amplitude-modulation system had full deviation of seventy-five kilocycles been employed but, on the occasion, it was not possible to use a deviation of greater than twenty-five kilocycles. It was also observed at the same time that, when the plate voltage on the power amplifier was raised to give a power of the order of 200 watts in the antenna, a better signal-to-noise ratio was obtained than that which could be produced by the two-kilowatt amplitude modulation. A casual comparison of the power-amplifier stages of the frequency-modulation transmitter shown in Fig, 23 with the water-cooled power amplifier and modulation stages of the Empire State transmitter is more eloquent than any curves which may be shown herein.

In the broadcast service, no such choice of location is possible and a widely variable set of conditions must be met. Depending on the power at the transmitter, the elevation of the antenna, the contour of the intervening country, and the intensity of the interference, there will be a certain distance at which peaks of ignition noise become greater than the carrier. The irregularity and difficulty of reproduction of these disturbances require a different method of comparison which will be hereinafter described.

As the site at Westhampton which was on a section of the beach remote from man-made static was obviously too favorable a site, a new one was selected at Haddonfield, New Jersey and, about the end of June, the receiving apparatus was moved there and erected at the home of Harry Sadenwater. Haddonfield is located about eighty-five miles from New York in the vicinity of Camden, New Jersey, and is over 1000 feet below line of sight of the top of the Empire State Building in New York. Although the field strength at Haddonfield was considerably below that of Westhampton beach, good reception was obtained almost immediately; the sole source of noise heard being ignition noise from a few types of cars in the immediate vicinity of the antenna, or lightning striking within a few miles of the station. At this distance, fading made its appearance for the first time, a rapid flutter varying in amplitude three- or four-to-one being frequently observable on the meters. The effect of it was not that of the selective fading so well known in present-day broadcasting. Very violent variations as indicated by the meters occurred without a trace of distortion being heard in the speaker. During a period of over a year in which observations have been made at Haddonfield, but two short periods of fading have been observed where the signal sank to a level sufficient to bring in objectionable noise, one of these occurring prior to an insulation failure at the transmitter.

It is a curious fact that the distant fading, pronounced though it may have been at times, is not so violent as that which may be encountered at a receiving station located within the city limits of New York. The effect, which appears to be caused by moving objects in the vicinity of the receiving antenna, causes fluctuations of great violence. It was apparently first observed by L. F. Jones, of the RCA Manufacturing Company, within a distance of half-a-mile of the Empire State transmitter. It occurs continually at Columbia University, located about four miles from the Empire State transmitter, but no injurious effect on the quality of the transmission has ever been noted.

While, at first, because of the lower field strength at Haddonfield and the greater prevalence of ignition disturbances, the superiority over the regular broadcast service was not so marked as at Westhampton Beach; the subsequent improvements which were instituted at both transmitting and receiving ends of the circuit have more than offset the lower signal level. Some idea of their extent may be gained by comparison of the initial and final antenna structures. Figure 24 shows the original antenna during the course of erection, a sixty-five foot mast bearing in the direction of New York permitting the use of an eight-wave-length sloping wire of very useful directive properties. Figure 25 shows the final form on which the results are now much better than were originally obtained with the directional wire.

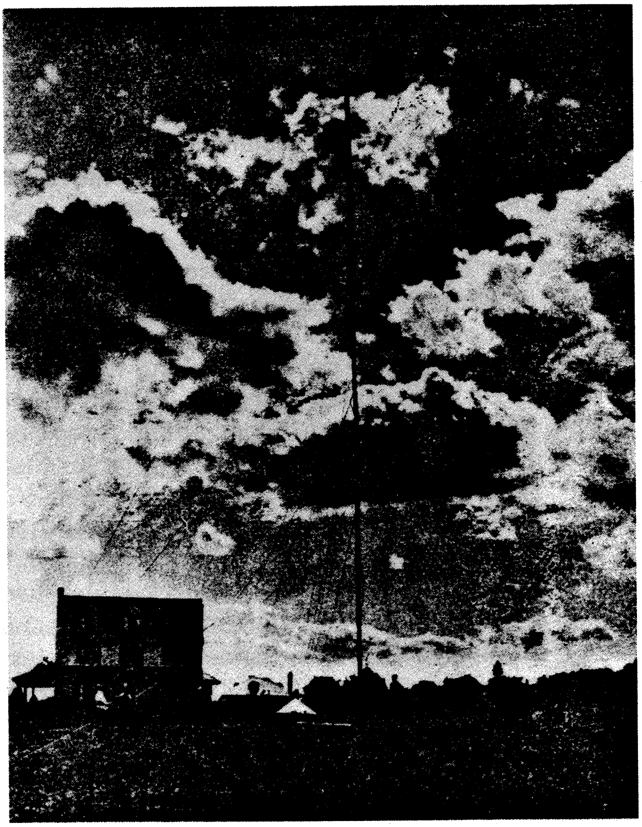


Fig. 24

During the past summer which was marked by thunderstorms of great severity in the vicinity of Philadelphia, it was the exception when it was agreeable or even possible to listen to the nightly programs of the regular broadcast service from the fifty-kilowatt New York stations.

In some of the heaviest storms when lightning was striking within the immediate vicinity of the antenna, so close in fact that the leadin was sparking to a nearby water pipe, perfectly understandable speech could be received on the frequency-modulation system although the disturbance was sufficient to cause annoyance on a musical program; but these periods seldom lasted more than fifteen minutes when the circuit would again become quiet. On numerous occasions, the Empire State signal was better than that of the fifty-kilowatt Philadelphia station WCAU located at a distance of twenty miles from Haddonfield. Likewise, during periods of severe selective side-band fading in the broadcast band which occurs even from station WJZ at Bound Brook, New Jersey, some sixty miles away, no signs of this difficulty would appear on the ultra-high-frequency wave.

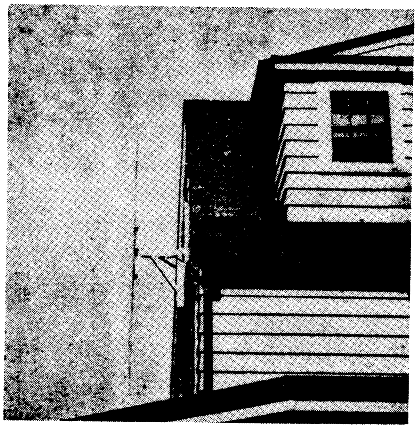


Fig. 25

Some of the changes which contributed to the improvement during the past year may be of interest. The introduction of the Thompson-Rose tube permitted the radio-frequency amplification required at forty-one megacycles to be accomplished with one stage and with considerable improvement of signal-to-noise ratio. It had a further interesting result. The tubes previously used for amplifying at this frequency were those developed by the Radio Corporation for the ultra-short-wave inter-island communication system in the Hawaiian Islands. On account of the relatively low amplification factor of these tubes, the shot effect in the plate circuit of the first tube exceeded the disturbances due to thermal agitation in the input circuit of that tube by a considerable amount. With the acorn-type tube, however, the situation is reversed, the thermal noise contributing about seventy-five percent of the rectified output voltage.

It should be noted here by those who have occasion to make this measurement on a frequency-modulation system that it cannot be made in the ordinary way by simply mis-tuning the input circuit to the first tube. To do so would remove the carrier from the current limiter and be followed by a roar of noise. The measurement must be made with a local signal of the proper strength introduced into one of the intermediate-frequency amplifiers. Under these conditions, the antenna may be mistuned without interfering with the normal action of the limiter and the relative amounts of noise due to the two sources may readily be segregated.

Considerable trouble was caused during the early stages of the experiments by an order of the Federal Radio Commission requiring the changing of frequency of the Empire State transmitter from forty-four to forty-one megacycles; this necessitating the realignment of the large number of interstage transformers in the modulating equipment shown in Fig. 20 and also the retermination of the antenna. It, however, led to the application of the idea inherent in superheterodyne design.

While the circuits of the old modulator were temporarily modified and work carried on, a new modulation system was designed standardizing on an initial frequency of 100 kilocycles which was then multiplied by a series of doublers up to 12,800 kilocycles. By means of a local oscillator, this frequency was heterodyned down to 1708 kilocycles, the new value of input frequency to the transmitter required to produce forty-one megacycles in the antenna. Any future changes in wave length can be made by merely changing the frequency of the second oscillator. The frequencies chosen were such that a deviation of 100 kilocycles could be obtained without difficulty because of the extra number of frequency multiplications introduced. Figure 26 shows the two modulation systems during the process of reconstruction with arrangements for making the necessary step-by-step comparisons between them.

Much attention was paid during the year to the frequency characteristic of the transmitter which was made substantially flat from thirty to 20,000 cycles. This required careful attention to the characteristics of the doubler and amplifier circuits of the transmitter and, to John Evans of the RCA Manufacturing Company and to T. J. Buzalski, I am indebted indebted for its accomplishment.

Continuous improvement of the transmitter and antenna efficiency was effected throughout the year but of this phase of development, R. M. Morris of the

National Broadcasting Company under whose direction the work was carried on, is better qualified to speak. As the final step, the lines connecting the transmitter with the control board of the National Broadcasting Company at Radio City from which the test programs were usually supplied, were equalized to about 13,000 cycles and when this had been done, the quality of reception at Haddonfield was far better than that obtainable from any of the regular broadcast stations.

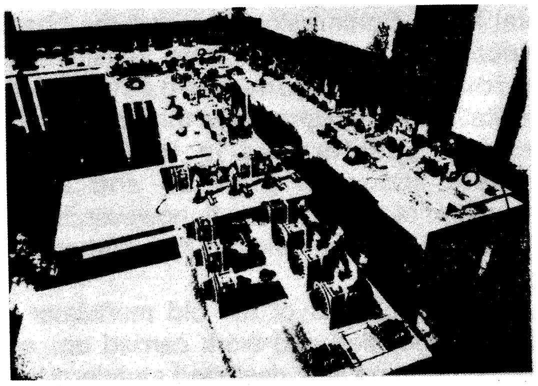


Fig. 26

INTERFERENCE AND FADING

Reference has heretofore been made to the difficulty of comparing the amounts of interference produced in amplitude- and frequency-modulation systems by the transient type of disturbance, particularly when, as in ignition noise, the peaks are greater than the signal carrier. The best method of comparison seems to be that of observing how much greater signal level from the standard signal generator must be introduced into the receiving system when it is arranged to receive amplitude modulation than is required for the same signal-to-noise ratio on a frequency-modulated system. The experimental procedure of making such comparison is to change the connection of the speaker rapidly from one receiver to the other, simultaneously changing the level of the local generator until the two disturbances, as perceived by the ear, are equal. At all times, of course, the amplification in the amplitude-modulation receiver is correspondingly changed as the signal-generator level is varied to apply the same voltage to the amplitude- as to the frequency-modulation detector so that the audio-frequency signal level which will be produced by the two systems is the same. The square of the ratio of the two voltages of the signal generator gives the factor by which the *carrier* power of the amplitude-modulated transmitter must be increased to give equal performance. While the measurement is difficult to make, the following approximations may give some idea of the magnitudes involved.

If the peak voltage of the ignition noise is twice the carrier level of the frequency modulation system, about 150 to 200 times the power must be used in the carrier of the amplitude-modulation system to reduce the disturbance level to the same value. When the peak voltage is five times as great, about 35 to 40 times the power in the amplitude-modulation carrier is sufficient to produce equality.[17] These observations have been checked aurally and by oscilloscope. The results of the measurements where the disturbances are due solely to the thermal and shot effects have been compared to those obtained with the method previously described and are found to check with it.

The chief value of this method of measurement, however, lies in the ability to predict with certainty the signal level required to suppress all ignition noise. An experimental determination made at Haddonfield shows that a signal introduced from the local generator which produces at the current limiter ten times the voltage of the Empire State signal, is sufficient to suppress the disturbance caused by the worst offender among the various cars tested. These cars were located as closely as possible to the doublet antenna shown in Fig. 25, the distance being about forty feet.

The increase in field strength necessary to produce this result can be readily obtained by an increase in the transmitter power to twenty- or twenty-five kilowatts and the use of a horizontally-directional antenna array. An increase in the field strength of three- or four-to-one by means of an array is within the bounds of engineering design so that the practical solution of the problem of this type of interference is certainly at hand up to distances of one hundred miles.

So also is the solution of the problem at its source. It has been determined experimentally that the introduction of 10,000 ohms (a value of resistance which is not injurious to motor performance) into the spark plug and distributor leads of the car referred to eliminates the interference with the Empire State signal.

Since active steps are now being taken by the manufacturers of motor cars to solve the more difficult general problem, the particular one of interference with sets located in the home will thus automatically disappear. The problem of eliminating the disturbance caused by an automobile ignition system in a receiving set whose antenna is a minimum of fifty feet away from the car is obviously a much simpler one than that of eliminating interference in a receiver located in the car or in another car a few feet away.

During the course of the experimental work in the laboratory, a very striking phenomena was observed in the interference characteristics between frequency-modulation systems operating within the same wave band. The immunity of a frequency-modulation system from interference created by another frequency-modulated transmission is of the same order of magnitude as the immunity with regard to tube noises.

This property merits the most careful study in the setting up of a broadcast system at those wave lengths at which the question of inter-station interference is a major factor. It is well known that when the carriers of two amplitude-modulated transmitters are sufficiently close in frequency to produce an audible beat, that the service range of each of them is limited to that distance at which the field-strength of the distant station becomes approximately equal to one per cent of the field-strength of the local station. As a consequence of this, the service area of each station is very greatly restricted; in fact, the service area of the two combined is but a small percentage of the area which is rendered useless for that frequency due to the presence thereon of the two interfering stations.

With the wideband frequency-modulation system, however, interference between two transmissions does not appear until the field-strength of the interfering station rises to a level in the vicinity of fifty per cent of the field-strength of the local one. The reason for this lies in the fact that, while the interfering signal is beating with the current of the local station under such conditions may be producing a fifty-percent change in the voltage applied to the current limiter, the system is substantially immune to such variations in amplitude. The only way in which the interfering signal can make its presence manifest is by cross-modulation of the frequency of the local signal. Since, under the conditions, this cross-modulation produces less than a thirty-degree phase shift and since the characteristics of the wide-band receiver are such that, at least within the range of good audibility, thousands of degrees of phase shift are necessary to produce full modulation, it is clear that a thirty-degree shift will not produce very much of a rectified output. For example, assuming two unmodulated carriers are being received, that their amplitudes have a ratio of two-to-one and that their frequencies differ by 1000 cycles, then for a system having a wide band (of the order of 150,000 cycles) the modulation produced by the interaction of the two carriers would be of the order on one per cent of that produced by full modulation of the stronger carrier.

This example, however, represents perhaps the worst possible condition as, during modulation of either station with the proper type of conversion system, the aural effect of the disturbance is greatly reduced. The whole problem of interference between unmodulated carriers may, however, be entirely avoided by separating them in frequency by an amount beyond the audible range. Hence it follows that with two wide-band frequency-modulated transmitters occupying the same frequency band, that only the small area located midway between the two wherein the field strength of one station is less than twice the field strength of the other will be rendered useless for reception of either station.

This area may well be less than ten per cent of the total area. Even in this area, reception may be effected as a receiving station located within it has only to erect directional aerials having a directivity of two-to-one to receive either station. The two-to-one ratio of field strength which has been referred to as the ratio at which interference appears is not by any means the limit but rather one which can be realized under practically all conditions. Better ratios than this have been observed but the matter is not of any great importance since, by the use of directional antennas referred to, it becomes possible to cover the sum of the areas which may be effectively covered by each station operating alone, subject only to the limitations of the noise level. The problem of the interference due to overlapping has been completely wiped out. One precaution only should be observed -- the unmodulated carriers should be offset in frequency by an amount beyond the audible limit.

In the above analysis it has been assumed, of course, that the distance between the stations has been selected so that the "no-mans land" between stations is not sufficiently distant from either one to be within the zone where any large amount of fading occurs. If the distance between stations is such that the signal strength varies appreciably with time then the directivity of the receiving antennas must be greater than two-to-one.

DIFFICULTIES AND PRECAUTIONS

The principles which have been described herein were successfully applied only after a long period of laboratory investigation in which a series of parasitic effects that prevented the operation of the system were isolated and suppressed. The more important of these effects which will be of interest to those who may undertake work in this field, will be referred to briefly.

It was observed in the early work in the laboratory that it was, at times, impossible to secure a balance in the detector system, and that the amplitudes of the currents in the rectifiers varied in very erratic fashion as the frequency of the first heterodyne was changed. Under these conditions, it was not possible to produce any appreciable noise suppression. The effect varied from day to day and the cause defied detection for a long period of time. Ultimately, the presence of two side-frequencies in the detector circuits was discovered, one of these frequencies lying above and the other below the unmodulated intermediate-frequency by an amount equal to the initial crystal frequency of the transmitter.

It was then discovered that the trouble had its origin in the transmitting system and that a current having the fundamental frequency of the crystal (in the present case 57.33 kilocycles), passed through the first doubler circuits in such phase relation to the doubled frequency as to modulate the doubled frequency at a rate corresponding to 57.33 kilocycles per second. This modulation of frequency then passed through all the transmitter-doubler stages, increasing in extent with each frequency multiplication and appearing finally in the forty-four-megacycle output as a fifty-seven-kilocycle frequency modulation.

In the first-doubler tank circuit of the transmitter, a very slight change in the adjustment of the tuning of the circuit produced a very great change in the magnitude of this effect. A few degrees shift in the tuning of the first-doubler tank condenser, so small that an almost unnoticeable change in plate current of the doubler occurred, would increase the degree of modulation to such extent as to make the first upper- and lower-side frequencies in the forty-four-megacycle current greater than the carrier or mid-frequency current (when no audio modulation was applied.) Under such conditions the proper functioning of the receiving system was impossible.

The delay in uncovering this trouble lay in the fact that it was obscured by the direct effect of harmonics from the transmitter doubler stages which had to be set up in an adjoining room and by the numerous beats which can occur in a double-intermediate-frequency superheterodyne. To these effects were added an additional complication caused by the presence of harmonics of the selective system resulting from the action of the limiter which the filtering arrangements did not entirely remove. The coincidence of one of these harmonics with the natural period of one of the inductances in the branch circuits likewise interfered with the effectiveness of the noise suppression. The causes of all these spurious effects were finally located and necessary steps taken to eliminate them.

With the removal of these troubles, a new one of a different kind came to light and, for a time, it appeared that there might be a very serious fundamental limitation in the phase-shifting method of generating frequency-modulation currents. There was found to be in the output of the transmitter at forty-four megacycles, a frequency modulation which produced a noise in the receiver similar to the usual tube hiss. The origin of it was traced to the input of the first doubler or the output of the crystal oscillator where a small deviation of the initial frequency was produced by disturbances originating in these circuits. While the frequency shift in this stage must have been very small, yet on account of the great amount of frequency multiplication (of the order of 800 times), it became extremely annoying in the receiver; in fact, for low levels of receiver noise, that noise which originated in the transmitted wave was by far the worse.

For a time, it seemed as though the amount of frequency multiplication which could be used in the transmitter was limited by an inherent modulation of the frequency of the oscillator by disturbances arising in the type itself. The proper proportioning of the constants of the circuit, however, reduced this type of disturbance to a point where it was no longer of importance, and frequency multiplications as high as 10,000 have since been effectively used. On account of the very large amount of frequency multiplication, any troubles in these low-frequency circuits caused by noisy grid leaks, improper by-passing of power-supply circuits, or reaction of one circuit upon another become very much more important than they would normally be. Difficulties of all kinds were encountered, segregated, and eliminated.

Another source of trouble was discovered in the correction system. Because of the range of frequency required particularly in multiplex work where thirty to 30,000 cycles was frequently used, the output voltage of the correction system at the higher frequencies became very much less than the input voltage, hence any leakage or feed-forward effect due to coupling through the power-supply circuits developed a voltage across the output much higher than that required by the inverse-frequency amplification factor as determined by the correction network. Hence, the frequency swing for the upper frequencies of modulation would frequently be several hundred per cent greater than it should be. Likewise, at the lower end of the scale, various reactions through the power supply were very troublesome. All these effects, however, were overcome and the correction system designed so that its accuracy was within a few per cent of the proper value.

From the foregoing it might be assumed that the transmitting and receiving apparatus of this system are inherently subject to so many new troubles and complications that their operation becomes impracticable for ordinary commercial applications. Such is not the case. The difficulties are simply those of design, not of operation. Once the proper precautions are taken in the original design, these difficulties never occur except as occasioned by mechanical or electrical failure of material. During the period of over a year in which the Empire State transmitter was operated, only two failures chargeable to the modulating system occurred. Both were caused by broken connections. Even the design problems are not serious as methods are now available for detecting the presence of any one of the troubles which have been here enumerated. These troubles were serious only when unsegregated and, *en masse,* they masked the true effects and made one wonder whether even the laws of electrical phenomena had not been temporarily suspended.

MULTIPLEX OPERATION

During the past year, two systems of multiplexing have been operated successfully between New York and Haddonfield and it has been found possible to transmit simultaneously the Red and Blue Networks' programs of the National Broadcasting Company, or to transmit simultaneously on the two channels, the same program. This last is much simpler thing to accomplish as the cross-talk problem is not a serious one. The importance of multiplexing in point-to-point communication services has long been recognized. In broadcasting, there are several applications which, while practical applications may be long deferred, are clearly within view.

Two general types of multiplexing were used. In one type, a current of superaudible frequency is caused to modulate the frequency of the transmitted wave. The frequency at which the transmitted wave is caused to deviate is the frequency of this current, and the extent of the deviation is varied in accordance with modulation of the amplitude of the superaudible frequency current.

At the receiver, detection is accomplished by separating the superaudible current and its component modulations from the rectified audible-frequency currents of the main channel and reproducing the original modulating current from them by a second rectification. The general outline of the system is illustrated in Figs. 27 and 28.

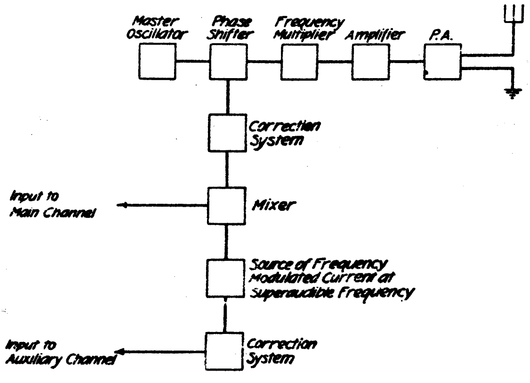


Fig. 27

The setting of the levels of the main and auxiliary channels must be made in this system of modulation with due regard to the fact that the deviation of the transmitted wave produced by the superaudible-frequency current of the second channel is a variable one, and changes between the limits of zero and double the unmodulated deviation.

In the second method of multiplexing, a superaudible current produces a frequency modulation of the transmitted wave of constant deviation, the rate of deviation being varied in accordance with the frequency of the superaudible current, and modulation being produced by varying the frequency of this auxiliary current and, thereby, the rate at which the superimposed modulation of frequency of the transmitted wave changes.

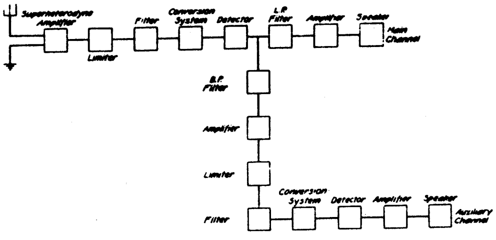

Superheterodyne Amplifier
Limiter
Filter
Conversion System
Detector
L.P. Filter
Amplifier
Speaker
Main Channel
B.P. Filter
Amplifier
Limiter
Filter
Conversion System
Detector
Amplifier
Speaker
Auxiliary Channel

Fig. 28

The operations which must be carried out at the receiver are the following: after suitable amplification, limiting and filtering, an initial conversion and rectification produces in the output of the detector the audible frequencies of the main channel, and a super-audible, constant-amplitude variable-frequency current. This last is selected by means of a band-pass filter, passed through a second conversion system to translated the changes in the frequency into variations of amplitude, and then rectified to recreate the initial modulating current of the auxiliary channel. The general arrangement of the system is illustrated in Figs. 29 and 30.

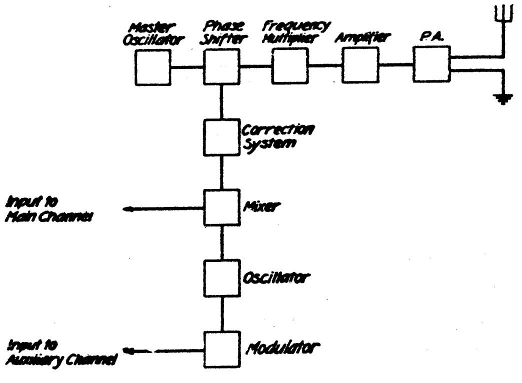

Master Oscillator
Phase Shifter
Frequency Multiplier
Amplifier
P.A.
Correction System
Input to Main Channel
Mixer
Oscillator
Input to Auxiliary Channel
Modulator

Fig. 29

This latter method of multiplexing has obvious advantages in the reduction of cross-modulation between the channels, and in the fact that the deviation of the transmitted wave produced by the second channel is constant in extent, an advantage being gained thereby which is somewhat akin to that obtained by frequency, as compared to amplitude, modulation in simplex operation. The subject of the behavior of these systems with respect to interference of various sorts is quite involved and will be reserved for future treatment as it is beyond the scope of the present paper.

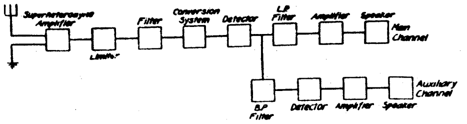

Superheterodyne Amplifier
Limiter
Filter
Conversion System
Detector
L.P. Filter
Amplifier
Speaker
Main Channel
B.P. Filter
Detector
Amplifier
Speaker
Auxiliary Channel

Fig. 30

The final arrangement of the modulating equipment installed at the Empire State station is illustrated in Figs. 31 and 32.

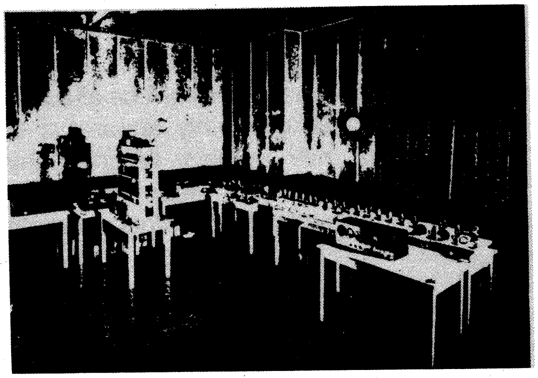


Fig. 31

The main channel apparatus is shown on the five tables located on the right side of the room. The vertical rack in the center contains three channels for transmitting facsimile by means of the amplitude-modulation method of multiplexing already described.

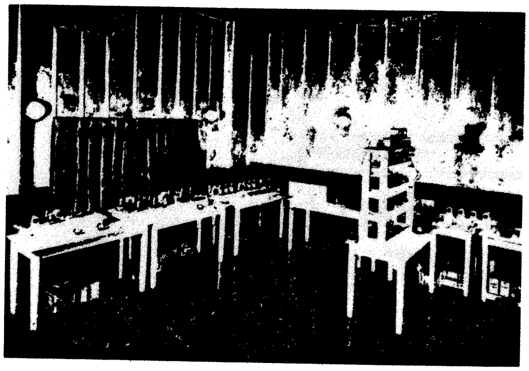


Fig. 32

In Fig. 32, located on the four tables on the left of the room is shown the auxiliary channel of the frequency-modulation type already described. The comparatively low frequency of this channel was obtained by the regular method of phase shifting and frequency multiplication, the frequency multiplication being carried to a high order and the resultant frequency-modulated current heterodyned down to twenty-five kilocycles (mid frequency.) A deviation up to ten kilocycles was obtainable at this frequency.

The receiving apparatus located at Haddonfield is illustrated in Figs. 33 and 34.

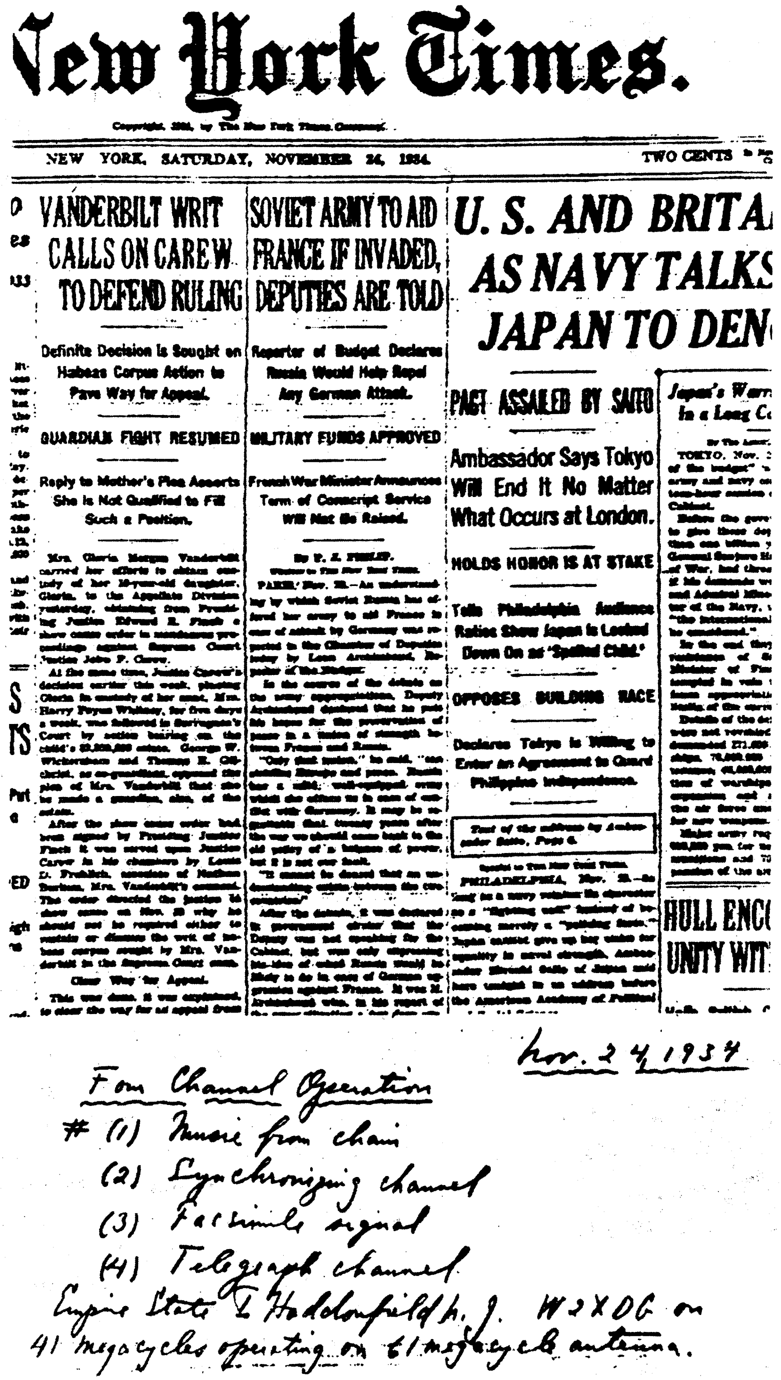
Fig. 33

Figure 33 shows the modified Westhampton receiver and 34 the multiplex channels of the receiver. The vertical rack to the right holds a three-channel receiver of the amplitude-modulation type. The two panels in the foreground constitute the frequency-modulation type of auxiliary channel.

Fig. 34

Some of the practical results may be of interest. It was suggested by C. Y. Young of the RCA Manufacturing Company that it might be possible to transmit simultaneously a facsimile service at the same time that a high-quality broadcast program was being transmitted. With the assistance of Mr. Young and Maurice Artzt, this was accomplished over a year between New York and Haddonfield, New Jersey, the two services operating without interference or appreciable loss of efficiency at the distance involved. Two additional channels, a synchronizing channel for the facsimile and a telegraph channel, were also operated. The character of the transmission is illustrated in Fig. 35, which shows a section of the front page of the *New York Times.*

This particular sheet was transmitted under considerable handicap at the transmitter as, due to a failure of the antenna insulator on the forty-one-megacycle antenna, it had become necessary to make use of the sixty-megacycle antenna for the forty-one-megacycle transmission. It is an interesting comment on the stability of the circuits that all four were kept in operation at the transmitter by one man, Mr. Buzalski, who was alone in the station on that day. The combined sound and facsimile transmission has been in successful operation for about a year, practically perfect copy being obtained throughout the period of the severe atmospheric disturbances of the past summer. The subject of the work and its possibilities can best be handled by Mr. Young who is most familiar with it.



New York Times.

Copyright, 1934, by The New York Times Company.

NEW YORK, SATURDAY, NOVEMBER 24, 1934. TWO CENTS

VANDERBILT WRIT CALLS ON CAREW TO DEFEND RULING

Definite Decision Is Sought on Habeas Corpus Action to Pave Way for Appeal.

GUARDIAN FIGHT RESUMED

Reply to Mother's Plea Asserts She Is Not Qualified to Fill Such a Position.

SOVIET ARMY TO AID FRANCE IF INVADED, DEPUTIES ARE TOLD

Reporter of Budget Declares Russia Would Help Repel Any German Attack.

MILITARY FUNDS APPROVED

French War Minister Announces Term of Conscript Service Will Not Be Raised.

U. S. AND BRITA

AS NAVY TALKS

JAPAN TO DEN

PACT ASSAILED BY SAITO

Ambassador Says Tokyo Will End It No Matter What Occurs at London.

HOLDS HONOR IS AT STAKE

Tells Philadelphia Audience Ratios Show Japan Is Looked Down On as 'Spoiled Child.'

OPPOSES BUILDING RACE

Declares Tokyo Is Willing to Enter an Agreement to Guard Philippine Independence.

Text of the address by Ambassador Saito, Page 6.

HULL ENC

UNITY WIT

Nov. 24 1934

Four Channel Operation

# (1) Music from chain

(2) Synchronizing channel

(3) Facsimile signal

(4) Telegraph channel

Empire State to Haddonfield N. J. W2XDG on
41 megacycles operating on 61 megacycle antenna.

Fig. 35

ACKNOWLEDGMENT

On account of the ramifications into which this development entered with the commencement of the field tests, many men assisted in this work. To some, reference has already been made.

I want to make further acknowledgment and express my indebtedness, as follows:

To the staff of the National Broadcasting Company's station W2XDG for their help in the long series of field tests and the conducting of a large number of demonstrations, many of great complexity, without the occurrence of a single failure;

To Mr. Harry Sadenwater, of the RCA Manufacturing Company, for the facilities which made possible the Haddonfield tests and for his help with the signal-to-noise ratio measurements herein recorded;

To Mr. Wendell Carlson for the design of many of the transformers used in the modulating equipment;

To Mr. M.C. Batsel and Mr. O.B. Gunby, of the RCA Manufacturing Company, for the sound film records showing the comparison at Haddonfield, of the Empire State transmission with that of the regular broadcast service furnished by the New York station;

To Mr. C.R. Runyon for his development of the two and one-half meter transmitters and for the solution of the many difficult problems involved in the application of these principles of modulation thereto; and

To Mr. T.J. Styles and particularly to Mr. J.F. Shaughnessy, my assistants, whose help during the many years devoted to this research has been invaluable.

CONCLUSION

The conclusion is inescapable that it is technically possible to furnish a broadcast service over the primary areas of the stations of the present-day broadcast system which is very greatly superior to that now rendered by these stations. This superiority will increase as methods of dealing with ignition noise either at its source or at the receiver, are improved.

APPENDIX

Since the work which has been reported in this paper on forty-one megacycles was completed, attention has been paid to higher frequencies. On the occasion of the delivery of the paper, a demonstration of transmission on 110 megacycles from Yonkers to the Engineering Societies Building in New York City was given by C.R. Runyon who described over the circuit, the transmitting equipment which was used. A brief description of this transmitter is reproduced here.

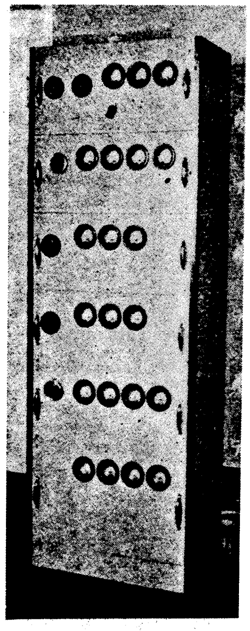


Fig. 36

The power delivered to the antenna was approximately 100 watts at 110 megacycles, and the deviation (one-half total swing) used during the demonstration was under 100 kilocycles. Fig. 35 illustrates the modulating equipment for this transmitter and the low-power frequency-multiplication stages. Fig. 36 shows the higher-power frequency multiplier and power-amplifier stages of the transmitter.

The rack shown in Fig. 35 consists of six panels. Panel number one at the top contains the correction system. Panel number two contains the master oscillator of 100 kilocycles and the modulator circuits. Panel number three contains a

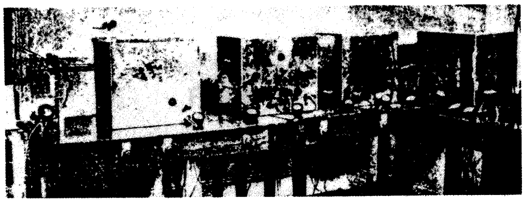


Fig. 37

pair of doublers for multiplying the 100-kilocycle frequency to 400 kilocycles and the necessary filtering means for avoiding the modulation of the currents in the succeeding doubler stages by the 100-kilocycle oscillator current. Panel number four contains the doubling apparatus for raising the frequency to 3200 kilocycles, and panel number five, the multipliers for raising it to 12,800 kilocycles.

Panel number five also contains a heterodyning and conversion system for beating the 12,800 kilocycles. Panel number six contains a doubler for raising this to 4584 kilocycles and an amplifier for increasing the level sufficiently to drive the succeeding power stage.

The output of this amplifier is fed through a transmission line to the metal box at the extreme right of Fig. 35 which contains a series of doublers and amplifiers for increasing the level and raising the frequency to 36,672 kilocycles. Adjacent to this box is a second box which contains a fifty-watt amplifier. This amplifier drives a tripler located in the third box and the tripler, in turn, drives the power amplifier located at the extreme left, at 110 megacycles. The transmitter circuits were designed for a total frequency swing of 500 kilocycles and may be effectively so operated. Because of the limitation of the receiver available at the time, the demonstration was carried out with a swing of 200 kilocycles.

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Eccles, "Wireless Telegraphy and Telephone," (1916).
Goldsmith, "Radio Telephony," (1918).

[2] "Notes on the Theory of Modulation," *Proc. I.R.E.*, vol. 10, pp. 57-82; February, (1922).

[3] Ueber Frequenzmodulation," *Telefunken-Zeitung* no. 53, p. 48, (1929).

[4] "Frequency Modulation," *Proc.I.R.E.*, vol. 18, pp. 1194-1205; July, (1930).

[5] "Amplitude, Phase, and Frequency Modulation, *Proc. I.R.E.*, vol. 19, pp. 2145-2176; December, (1931).

[6] "The Reception of Frequency Modulated radio Signals," *Proc. I.R.E.*, vol. 20, pp. 835-840; May, (1932).

[7] For the large angular displacements, there will be an appreciable change in amplitude of the combining currents at double the frequency of the modulating current. This variation in amplitude is not of primary importance and is removed subsequently by a limiting process.

[8] One in which the side frequencies are sufficiently large with respect to the carrier to make it possible to produce at the receiver 100 percent modulation in amplitude without the use of expedients which effect unfavorably the signal-to-noise ratio.

[9] J.R. Carson, "Selective Circuits and Static Interference," *Bell Sys. Tech. Jour.*, vol. 4, p.265, (1925).

[10] L.A. Hazeltine, Discussion on "The Shielded Neutrodyne Receiver," *Proc. I.R.E.*, vol. 14, pp. 408, 409; June (1926).

[11] J.B. Johnson, "Thermal Agitation of Electricity in Conductors," *Phys. Rev.*, vol. 32, no. 1, July, (1926).

[12] Stuart Ballantine, "Fluctuation Noise in Radio Receivers," *Proc. I.R.E.*, vol. 18, pp. 1377-1387; August, (1930).

[13] Ballantine expressed his result as follows: "In a radio receiver employing a square-law detector and with a carrier voltage impressed upon the detector, the audio-frequency noise, as measured by an instrument indicating the average value of the square of the voltage (or current), is proportional to the area under the curve representing the square of the over-all transimpedance (or of the transmission) from the radio-frequency branch in which the disturbance originates to the measuring instrument as a function of frequency and proportional to the square of the voltage."

[14] J.B. Johnson and F.B. Llewellyn, "Limits to Amplification," *Trans. A.I.E.E.*, vol. 53, no. 11, November, (1934).

[15] It has been pointed out by Ballentine[16] that it is improper to speak of the amplitude of a single component of definite frequency and that the proper unit is the noise per frequency interval. This is of course correct, but to facilitate the physical conception of what occurs in this system, the liberty is taken of referring to the noise components as though they were of continuous sine-wave form. The behavior of the system may be checked by actually introducing from a local generator, such components.

[16] "Fluctuation Noise in Radio Receivers," *Proc. I.R.E.*, vol. 18, pp. 1377-1387; August, (1930).

[17] Linear detection was used in the amplitude modulation receiver but no limiting was employed.

Volume 25 1948 No. 3

A STUDY OF THE OPERATING CHARACTERISTICS OF THE RATIO DETECTOR AND ITS PLACE IN RADIO HISTORY

By
Dr. Edwin H. Armstrong,
Professor of Electrical Engineering, Columbia University

Many years ago, beyond the memory of most of those who will read this paper, there occurred a remarkable incident in the technical history of radio. It occurred during the year 1914, shortly after the invention of the regenerative circuit.

That part of this assembly whose experience in radio dates back to those early days will recall the revolution that the regenerative circuit brought about in the communication art, as that art was then practiced with spark transmitters and crystal detectors. They will also recognize the incident which I am going to identify presently.

For that part of this assembly whose experience in radio does not go back to those early days, some historical background will help in the understanding of that incident.

To put yourself in the atmosphere of those days you must perform a difficult feat of mental gymnastics; that of jumping backward into the radio world of over thirty-five years ago, a world where telephony[1] and loudspeakers were unknown, where communication was confined to the American and Continental Morse codes as manifested in headphone whispers, and where the strength of the signal heard was completely dependent upon the amount of energy that could be captured from the passing electromagnetic wave by the receiving antenna. That energy, and that alone, was all that was available to move the diaphragm of the receiving telephones. In order to hear weak signals it was necessary to use painfully tight headphones, frequently with the equally uncomfortable necessity of holding one's breath for prolonged intervals.

The continuous wave now in universal use had barely entered the picture, and its merit as compared to the almost universally used spark system was the subject of a lively and then unresolved controversy. In 1912, it is safe to say, 99.9% of radio communication was carried on with spark transmitters and rectifying (crystal and Fleming valve[2]) or magnetic detectors. Not a tenth of one percent of the stations made use of the deForest audion (triode), and those that did use the audion were mostly stations of the amateurs.

Static interference was combatted by arranging that the number of sparks per second at the transmitter were regularly spaced and lay within the musical range, so that the note heard in the phones had a distinguishing musical characteristic. Controversy existed over whether the high pitched whistle of the one thousand spark per second transmitter was superior to the deeper chord-like tone of one sparking at the rate of only three to four hundred times a second.

About a dozen continuous wave stations (arc and alternator) were operating with limited success in the United States and Europe, for the "undamped" wave system was severely handicapped by lack of a satisfactory means of reception. The receiver most generally used was a curious device known as the "tikker" which, while comparable to or perhaps slightly better in sensitivity than the crystal, suffered from the overwhelming handicap that it produced an unclear, non-musical signal impossible to read through heavy static.[3] Although the important virtues of the rectifying detector-heterodyne had been discovered by Lee and Hogan, the difficulty of providing a heterodyning source, quiet and stable enough for reception of what were then considered weak signals, had held up the introduction of the heterodyne into commercial radio.

---

[1] Fessenden had demonstrated radio telephone transmission in the Fall of 1906, but as the modulation problem had not been solved, radio telephony as a practical entity was non-existent.

[2] Diode.

[3] In 1912 two commercial transoceanic circuits were in operation - the Clifden, Ireland - Glace Bay, Nova Scotia circuit (spark system) operated by the Marconi Company, and the San Francisco-Honolulu circuit (Poulsen arc system) operated by the Federal Telegraph Company. The reported power for the spark circuit was 125 kilowatts, and for the arc 30-60 kilowatts. Antennas hundreds of feet in height were used for reception on both systems. The receiving antennas on the Clifden - Glace Bay circuit were several thousand feet long to insure additional and directive pick-up properties.

For those who never had the experience of living in the strange world I have just described - where amplifiers of audio frequencies were unknown, where the amplification of radio frequencies was undreamed of, and where the generation of even moderate amounts of continuous wave power at frequencies in excess of 100 kilocycles was impossible - it will be difficult indeed to imagine the conditions under which the men in the art worked in those days.

And it will be still more difficult for them to grasp the incredible fact that the three element vacuum tube (audion), now in use in every transmitter and receiver in the world, had been invented six years before the period I have just described and yet lay idle and neglected and almost forgotten.

If you will examine the pages of seven leading text books published prior to 1914 you will find that out of a total of three thousand pages for the seven volumes less than one page of material for the lot is devoted to the audion detector.[4] Some of the authors make no reference to it at all and, where reference is made, the audion is described solely as a detector, slightly more sensitive than the Fleming valve.

The reason for this almost unbelievable situation lay in the following set of facts. The inventor of the audion had never understood the operation of his device. Nor did anyone else in radio understand it, for the idea that there might be such a thing as an electron discharge had not penetrated into the art. As a result, some weird theories of the operation of the audion were advanced. In the inventor's version, gaseous ions were supposed to carry the current across the gap from filament to plate. The action of the audion was casually disposed of with the statement that the gaseous carriers were repelled upon the imposition of a negative charge on the grid, while the imposition of a positive charge enabled the grid to hold the ions in its vicinity, so that in either event a diminution of the plate current resulted.[5] This learned pronouncement had the effect of obscuring the potentialities of the audion as anything other than a detector of damped wave trains. Too long was the theory blindly accepted, without anyone taking the trouble to make a serious investigation to verify or disprove it.[6]

With the art in the state that I have described, there came in the Fall of 1912 the invention of the regenerative circuit. That circuit not only amplified the incoming radio frequency currents and increased the sensitivity hundreds or thousands of times, but also by reason of its ability to generate continuous oscillations with a stability and uniformity theretofore unknown, brought heterodyne reception to commercial perfection and ushered in a new era in long distance communication. In 1913 it had become possible in New York City, with an antenna of amateur dimensions, to receive spark and CW signals from European stations, as well as continuous wave signals from the West Coast of the United States and the Hawaiian Islands, and to demonstrate regularly such reception.[7]

So firmly entrenched was the "knowledge" in the art, however, that such things could not be, that most of those who listened to the signals were incredulous of their origin and those to whom the reports of such reception came by word of mouth greeted them with the same disbelief[8] that was to be accorded the announcement over twenty years later that an operative noise eliminator had at last been devised. Checks of copied messages with the stations originating them were required for what we might term today in our modern jargon "proof of performance", before the "reports" of transoceanic reception passed from the stage of disbelief openly expressed on the part of the leaders in the communication field to the stage where such reception became a commonplace in the art.

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[4] (Armstrong, letter to the New York Herald-Tribune, Dec. 21, 1930):
See: Kennelly's "Wireless Telegraphy and Telephony" 1909; Pierce's "Principles of Wireless Telegraphy" 1910; Fleming's "Principles of Electric Wave Telegraphy and Telephony" 1910; Zenneck's "Lehrbuck der Drahtlosen Telegraphie" 1912; Reins' "Radiotelegraphisches Praktikum" 1912; Erskine-Murray's "Handbook of Wireless Telegraphy" 1913; Edelman's "Experimental Wireless Stations" 1914.

[5] Proceedings I.R.E., March 1914, page 20, there appears the following statement by Lee DeForest:

> "If the charge thus impressed upon the grid be negative a repulsion or scattering of the negatively charged carriers emanating from the filament occurs. If the impressed charge be positive, then these carriers may be attracted to the grid and discharged there, or delayed in the neighborhood. In either case, therefore, a diminution in the number of ions reaching the plate results, and we observe a diminution in the deflection of a sensitive milliammeter or galvanometer in the "B" circuit when a prolonged series of impulses is delivered to the grid. ....
>
> "An insight into what forces are at work in the audion is afforded by experiments with a special circuit .... This experiment seems to show that in the normal operation of the Audion the imposition of a charge, negative or positive, upon the grid acts either to repel from its neighborhood the ionic carriers or to hold them idle there, thus in either case increasing the effective resistance in the filament-to-plate path."

Even after the operation of the audion had been fully explained by me in the Electrical World, December 12, 1914 in an article entitled "Operating Features of the Audion", and in a paper presented before the Institute of Radio Engineers, March 1915, the theory given in these articles was challenged by the inventor of the audion in the following language:

> "I have frequently proven that a positive as well as a negative charge will reduce the plate current."
> (Proceedings I.R.E., Sept. 1915, page 239).

[6] The single exception prior to the Summer of 1912 was Fritz Lowenstein, who made use of the audion in the Spring of that year as an amplifier of telephone currents. U.S. Patent 1,231,764.

[7] Ability to read the signals depended upon the level of the static at the time. Complete messages could usually be copied.

It was then that the incident I am about to discuss took place. After the regenerative circuit had been demonstrated to the leading communication companies and had passed its "proof of performance" test, there was announced the discovery of a device called the "ultraudion"[9]. It was claimed to perform the same functions as those of the regenerative circuit. However, it was held to perform them in a new way, not involving the regenerative principle. As a matter of fact, superficially, the circuits did look different.

The ultraudion circuit configuration was given as follows:

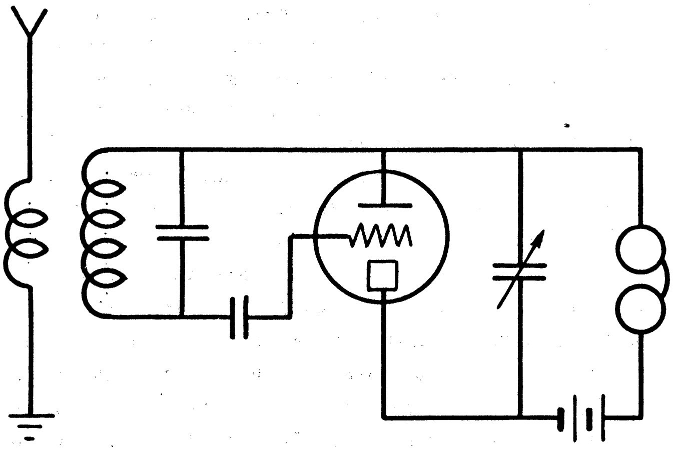

Fig. 1

In the words of its inventor, its manner of operation was described as follows:

> "The ultraudion circuit is not and cannot be a regenerative circuit. There is only one oscillating circuit. This circuit is such that a sudden change of potential impressed on the plate produces in turn a change in the potential impressed on the grid of such a character as to produce in its turn an opposite change of value of potential on the plate, etc. Thus the to-and-fro action is reciprocal and self-sustaining."[10]

With our present knowledge of vacuum tube circuits it is difficult to believe that even a part of the radio art could be long misled by this fantastic explanation. Yet so it was, and not until the circuit was analyzed in the light of factual understanding and was redrawn so that the coupling between the plate and grid circuits, as well as the part played by the grid-filament capacitances became manifest, was the operation of the ultraudion set forth in its true light.[11] The operation of the circuit as redrawn below is now, of course, accepted and understood by everyone.

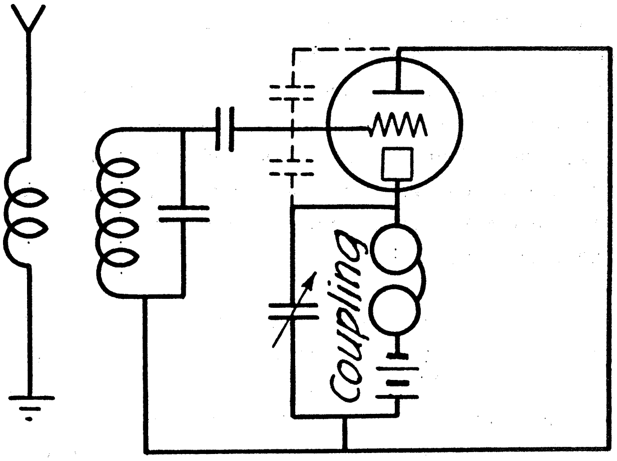

Fig. 2

I have related to you three instances of "Ripleyian" episodes in the past history of radio that a great many of you never heard about. Those of you who did not live through those early days may find it difficult to believe that the audion could have kicked around the art for six years without anyone, including the inventor, unlocking its secrets. You may likewise find it hard to visualize how only one page, out of three thousand in the leading radio textbooks, was devoted to the audion, or that anyone could have failed to perceive the quite obvious coupling between the input and output circuits of the ultraudion. But these things actually happened, and you can read about them in the literature. They were determinative of significant events which followed in the course of radio history. They are, in fact, basic radio history itself, and the course of events which they brought in their wake are worthy of most careful study.

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[8] See Appendix Two for an account of the response of the chief engineer of the world's greatest communication company - the American Telephone & Telegraph Company - when informed of the reception of signals from Honolulu at the Marcellus Hartley Research Laboratory at Columbia University by Professor Michael I. Pupin, then head of the Department of Electrical Engineering at the University.

[9] Electrical World, Feb. 20, 1914.

[10] Proceedings I.R.E., June 1916, page 266; Lee DeForest.

[11] Proceedings I.R.E., June 1916, Armstrong, pages 264, 265 and 266.
Proceedings I.R.E., April 1918, Hazeltine, page 87.
The idea of tube capacitance did not exist at the time. This may seem strange today, where interelectrode capacitances of vacuum tubes are taken into account as a matter of everyday design and where every college student studying communications knows all about them. However, in 1914 the idea that two little pieces of metal inside of a glass bulb could have capacitative properties in an amount that would have any effect on the operation of a radio circuit never occurred to anyone.

Now with these reminiscences of the ancient days of radio as a background for perspective, I want to introduce the subject of my talk this evening, with the statement that we have a modern counterpart of the ultraudion episode in the debut of what has been christened the "ratio detector".

As you all know, thirteen years ago I showed the art how to do something which was then considered impossible - how to eliminate noise. Values of noise reduction of 1000 to 1 in energy, as compared with the standard system of communication, were obtained, and I do not need to tell you that these figures were received with the same incredulity that greeted the reports of the results obtained with the regenerative circuit twenty years before.

Now, as with the regenerative circuit, the proof of performance tests have been passed and the facts of "FM" have become accepted as a part of our daily life. As with most "impossible" problems, the solution was achieved by a new approach. The discovery was described and the principles involved were presented in a paper delivered before the Institute of Radio Engineers in November 1935, and the following month before the Radio Club of America, and, of course, they are now well understood throughout the whole world.

For good reason the history of the application of FM to public use was quite unlike the history of the regenerative circuit. The regenerative circuit could be put into operation at once at the receiving end of all long distance communication circuits, with immediate improvement to the service and with relatively little expense. No change was required at the transmitter. Thus, as soon as its principle became known, it was widely installed in all transoceanic and naval communication circuits.

In the case of FM, on the other hand, new transmitters as well as new receivers were needed. A substantial financial outlay had to be undertaken. As in any new and significant departure from convention, forces of the kind attributable to men rather than to Nature had to be overcome. The value of the system was at first appreciated by only a relatively small number of individuals.[12]

General realization of the commercial value of FM was delayed for many years. But when its commercial value became apparent to everyone, history repeated itself and the modern counterpart of the ultraudion appeared on the scene in the form of the ratio detector. Let us now examine this seemingly technical innovation.

The "ratio detector" has been described in a paper presented before the Institute of Radio Engineers, and also in a bulletin issued by the RCA License Laboratory, wherein the statement was made that limiting was unnecessary and that amplitude modulations need not be removed in the receiver because of the "insensitiveness" of the device to such changes in amplitude. In that manner the representation was made to the industry that the ratio detector was something quite different in principle from the system that I had originated, in which amplitude variations are removed in order to suppress noise. As the paper before the Institute appears to have been withdrawn from publication, there has not been the usual opportunity for open, critical discussion of the mode of operation with all the serviceable clarification that such debate ordinarily engenders.

The ratio detector circuit as it was first published[13] was drawn as follows:

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[12] The basic noise suppression patent, issued December 26, 1933, explained how improvements in noise ratio of 100 to 1 or greater were to be obtained. Possibly because of the complexity of the subject, and also because a claim of 100 to 1 noise reduction was then considered too preposterous to be credited, no one - with the exception of those to whom the apparatus was demonstrated - paid the slightest attention to the patent.
At the June 1936 hearing of the Federal Communications Commission, six months after the presentation of my paper before the Institute of Radio Engineers, only two persons urged provision of space in the spectrum for FM broadcasting - Paul deMars, Technical Advisor of the Yankee Network, and the writer.
Leading text books published during the next several years repeated the statements that had been current for a decade or more, that Frequency Modulation was not a satisfactory method of modulation. See, for instance, Radio Engineering by Terman (1937) and Communications Engineering by Everett (1937).

[13] Fig. 2 of Bulletin No. 645 issued by the RCA License Laboratory entitled "Ratio Detector for F.M. Receivers."

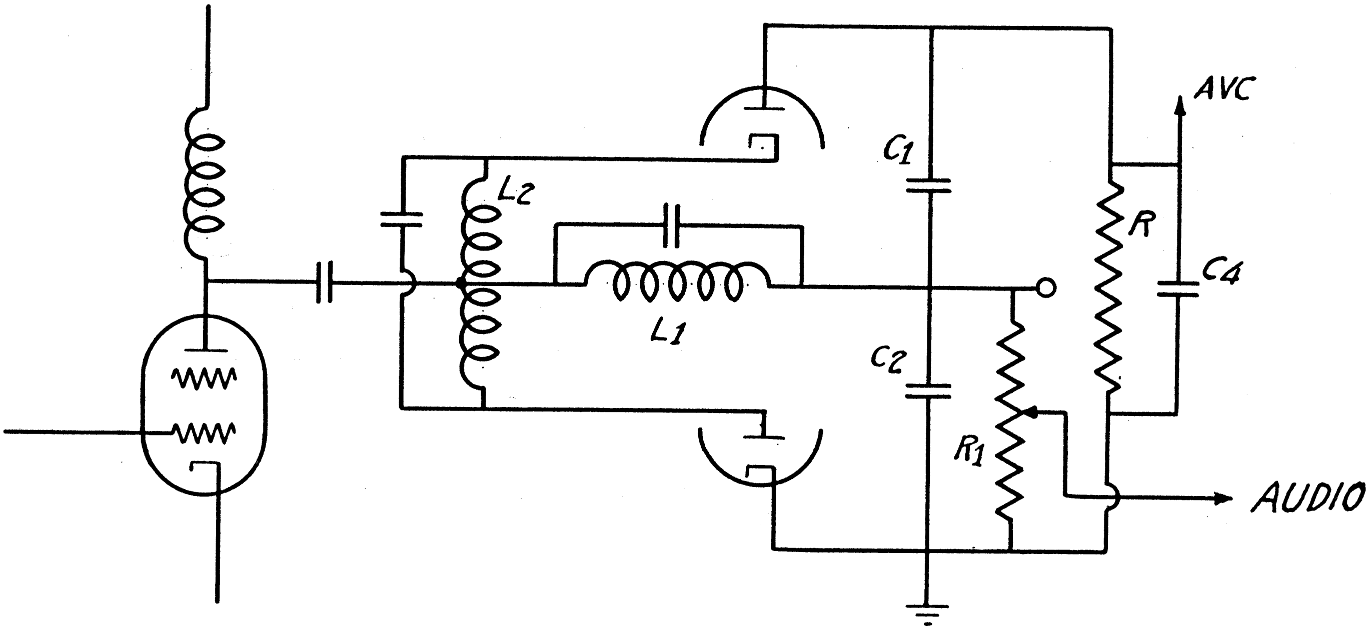

Fig. 3

In the particular form in which this circuit was drawn, any semblance to previous well known circuits was not apparent. The method of drawing the circuit, coupled with the fact that the explanation of the circuit's operation was, to say the least, obscure and unconventional, left one with the impression that an aura of mystery hung over this seemingly unfamiliar device.

Let us now redraw this curcuit, rearranging the elements in a more familiar manner, but preserving exactly the same electrical connections. This technique, as you have already seen, when it was applied to the ultraudion, removed the obscurity theretofore surrounding the behavior of the device. In the same way, rearrangement of the elements of the ratio detector will clarify the electrical operations of this circuit. Figure 4, which illustrates a rearrangement of the elements of Figure 3, is the same circuit as that shown in that figure, but as now drawn it begins to show a considerable resemblance to an ordinary two-path balanced discriminator circuit.

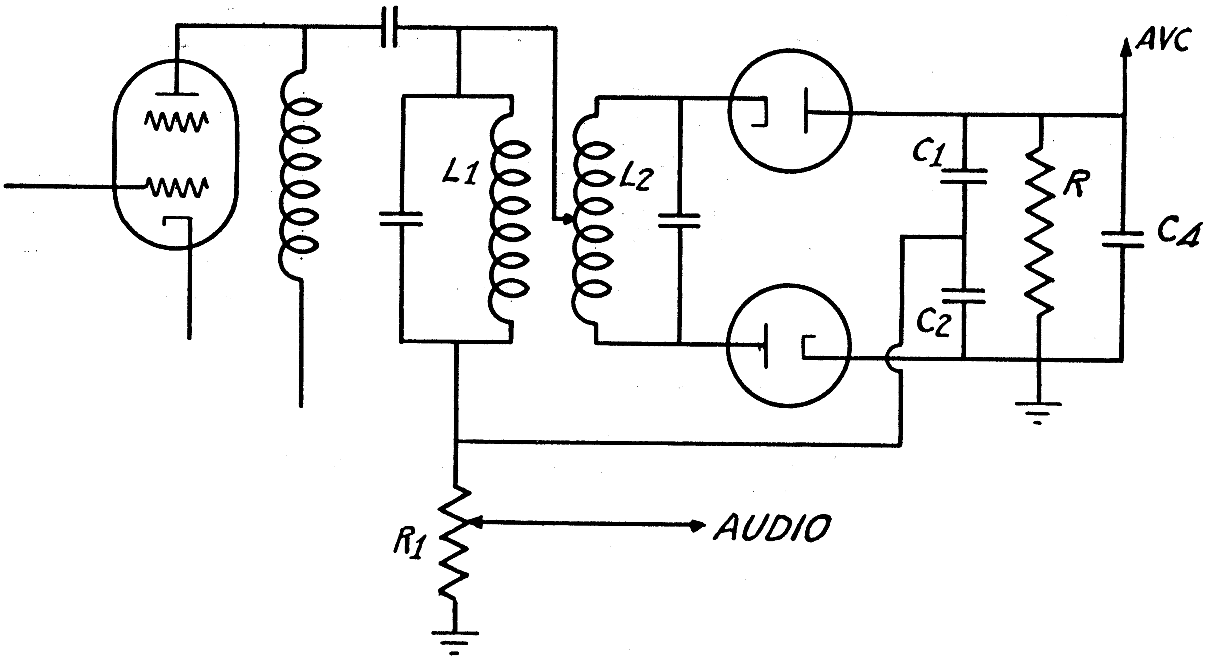

Fig. 4

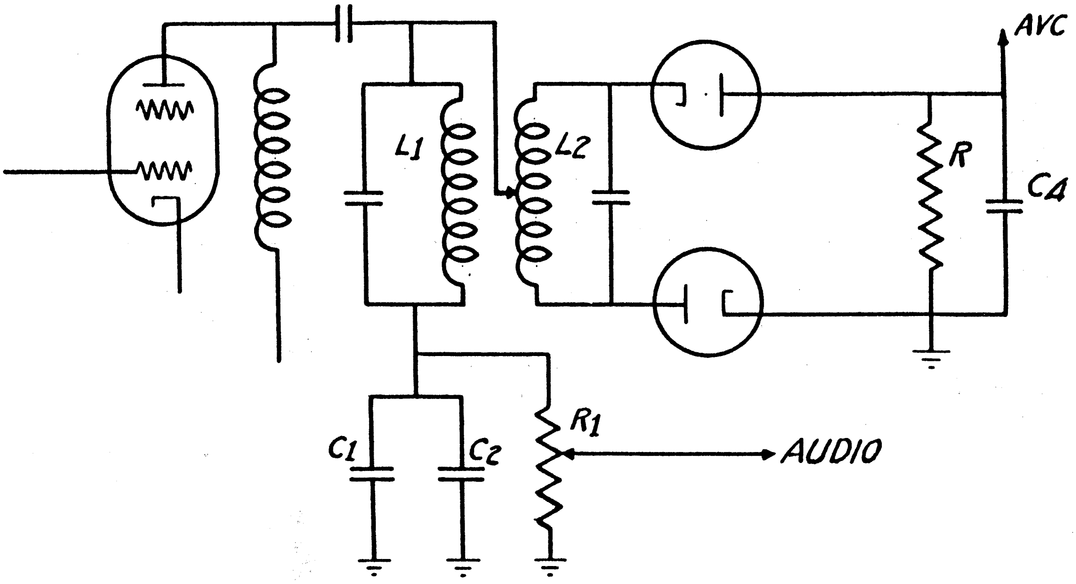

Fig. 5

Let us now take another step in the redrawing of the arrangement shown in Figure 4 without in any way changing the circuit, but merely rearranging the elements on the paper in a manner better adapted to portray the electrical characteristics of the circuit.[14] (See Figure 5)

Finally, let us redraw it as shown in Figure 6, merging the condensers C_1 and C_2 into a single unit, since it is now obvious these condensers are in parallel, and replacing the biasing elements RC_4 with biasing batteries B_1 and B_2, which, as the RCA Bulletin states, is the equivalent of the biasing combination RC_4.

Having clarified the original ratio detector circuit of Figure 3 by redrawing it in step by step fashion, it is now easy to look backward

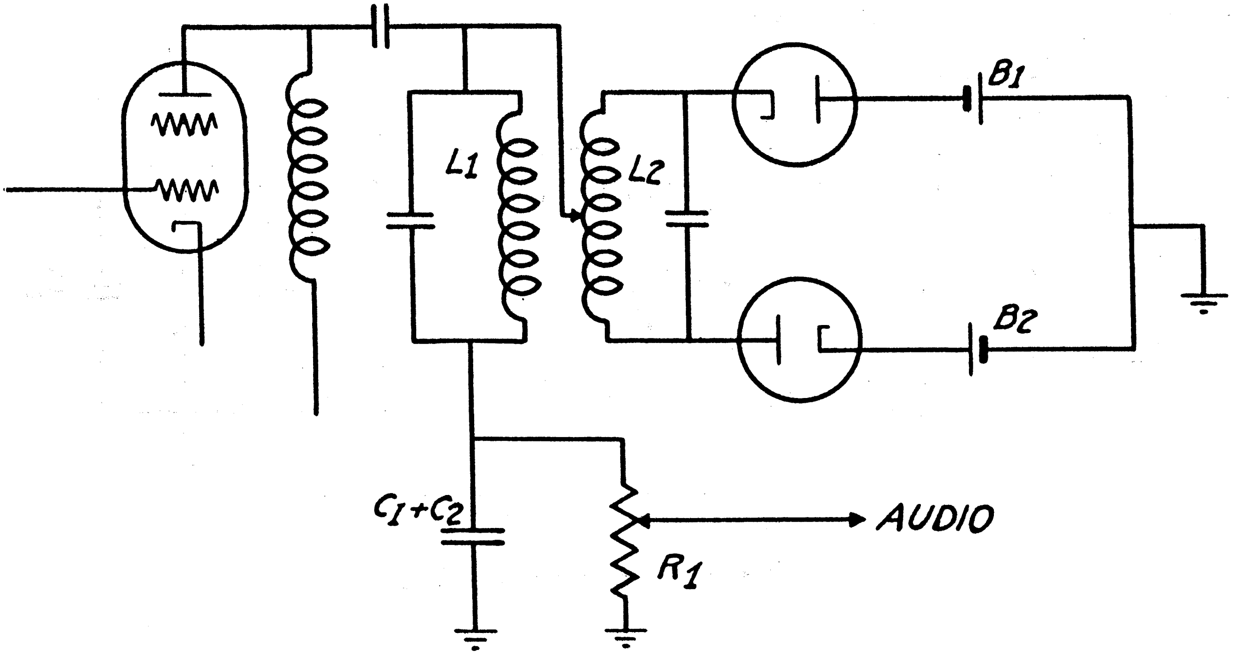

Fig. 6

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[14] (Neglecting, of course, the niceties of RF bypassing close to the diode elements.)

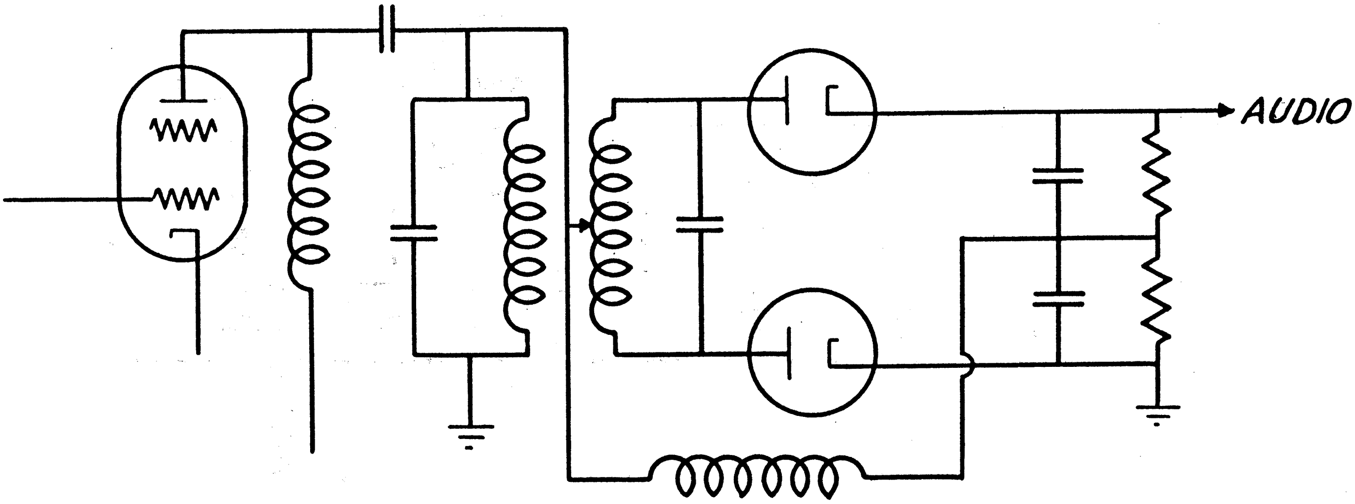


Fig. 7

and observe not only that the arrangement of Figure 6 is identical with Figure 3 but that its elements are arranged in such a way that the electrical functions of the device, instead of being obscured, are now well-on their way to becoming evident.

Let us now, for the purposes of comparison, examine a conventional discriminator circuit of Figure 7 shown herewith.

Disregarding for the moment the biasing voltages of the circuit of Figure 6, it is now evident that what has been done circuitwise in the "ratio detector" is merely the substitution of a current balanced type of rectification for the ordinary

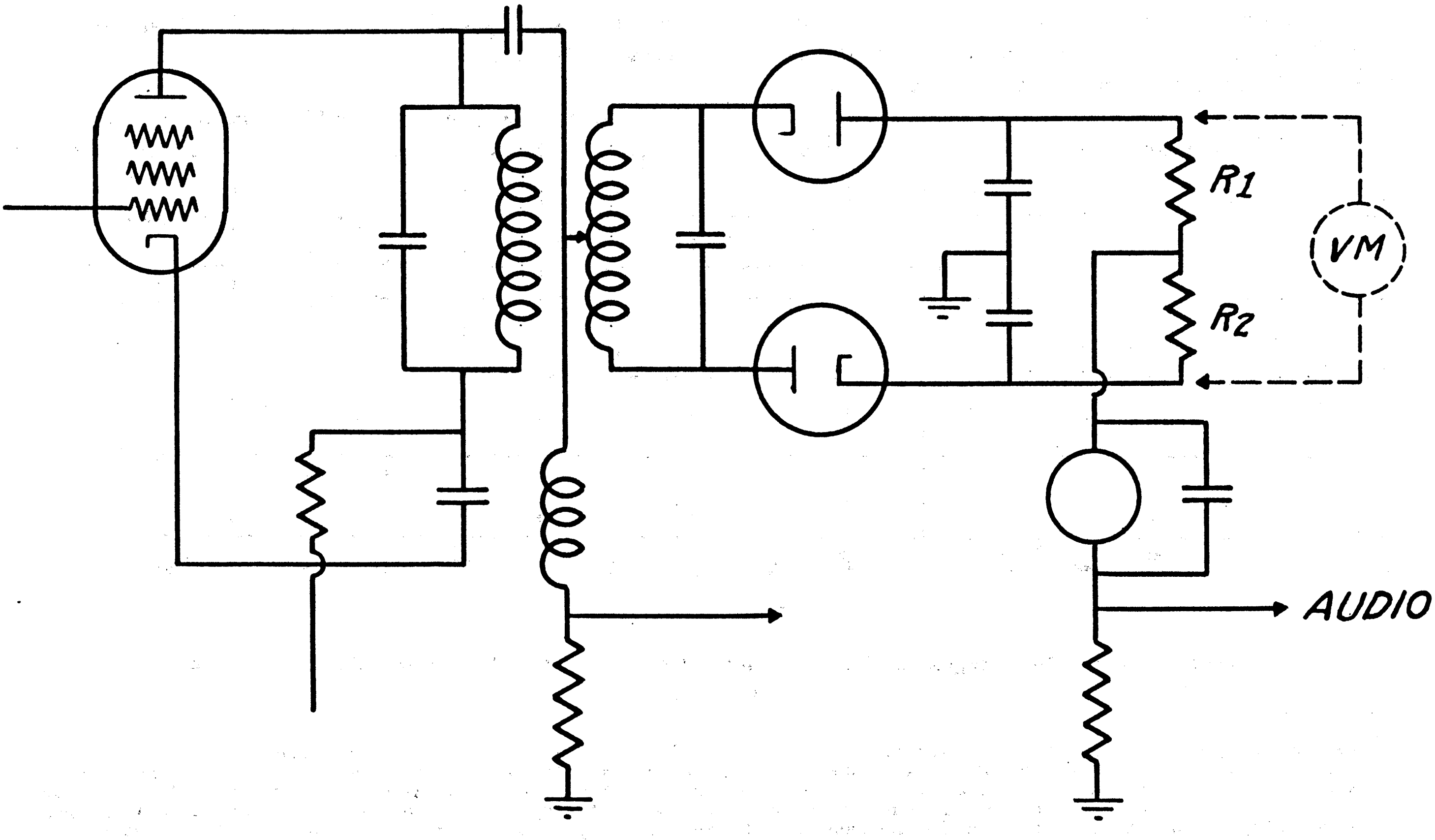


Fig. 8

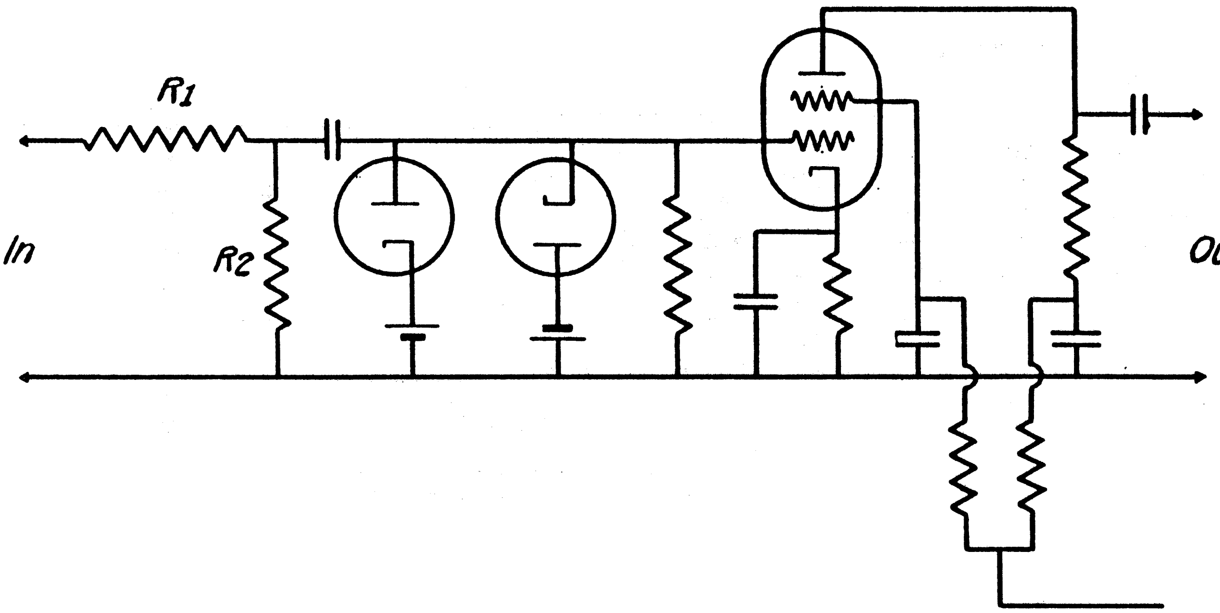


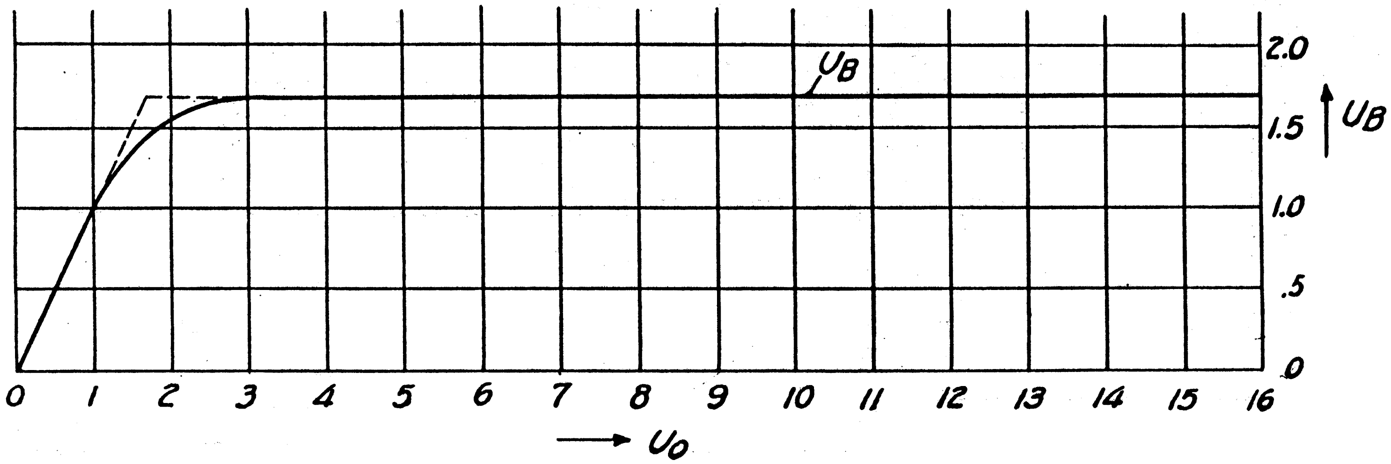
Fig. 9

voltage balanced type[15], something which is not at all novel in the art.[16]

The current balance type of discriminator has been used for a number of years in the General Electric FM Station Monitor. In the Summerhayes paper the author gives a straight-forward explanation of the action of the device which he labels "Current Sensitive Frequency Discriminator Circuit", and the reasons for using the current instead of the voltage balance. The circuit from the Summerhayes paper is reproduced in Fig. 8.

Wherein, then, does the operation of the "ratio detector" differ from the Summerhayes arrangement, since, with the exception of the biasing voltage obtained by the condenser-resistance combination RC_4 of Figure 4, they are diagrammatically the same?

To understand what really happens in the "ratio" detector circuit it is in order to go back



Author's Note. Two stages of limiting were used to obtain the above characteristic.

Fig. 10

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[15] As a matter of definition it is convenient to call the condition existing when separate currents flowing through separate impedance elements bring about a condition of zero voltage across the two elements a "voltage balance", and to call the condition a "current balance" when currents flowing in opposite direction through a single element cancel each other out to produce zero current through the common impedance. Of course the illustration is figurative only, as the physical picture in the case of a balance is simply that no current flows, and in the case of an unbalance that a residual or difference current passes through the common impedance.

[16] Proceedings I.R.E. June 1943, Summerhayes. Paper presented June 23, 1941.

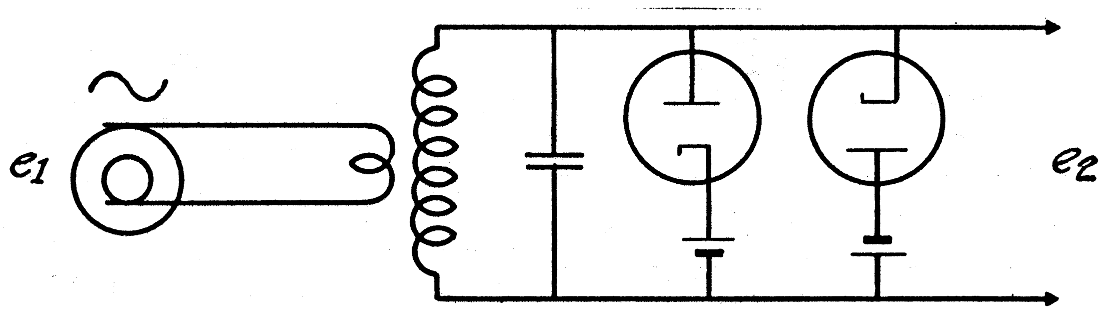


Fig. 11

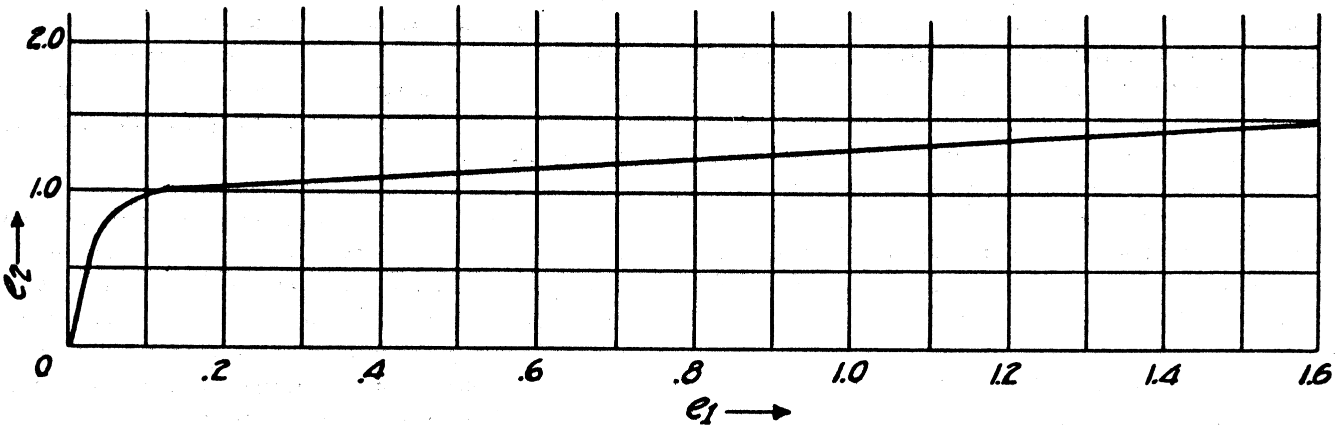
to a paper by Zuhrt[17] which reports an investigation of the F.M. phenomena presented to the Institute of Radio Engineers in my November 1935 paper. In this article Zuhrt describes a method of using diodes as limiters, the particular arrangement shown being reproduced herewith as Figure 9 (Zuhrt Fig. 19).

In this arrangement the biased-off diodes conduct after the level across resistance R_2 rises beyond a critical value, and by properly relating the various resistances to diode impedances a typical characteristic of the type shown in Figure 10 is obtained. (Zuhrt Fig. 20).

Although Zuhrt made use of resistors[18] in limiting the rise of voltage beyond the desired level, the principle is equally applicable to tuned circuits of the type indicated in Fig. 11 herewith, where a similar type characteristic as shown in Figure 12 is obtained.

It should now be apparent how the "ratio detector" operates. It is a device in which the limiting functions of the diode as disclosed by Zuhrt is made use of in the series diode connection of Summerhayes to give combined limiting and detection by means of a single tube. If there is any novelty in the device, it would seem to reside in the proportioning of the diode impedances to the characteristics of the discriminator circuit so that the function of removing amplitude variations - that is, limiting - becomes superimposed upon the function of detection.

The foregoing explanation of the operation of the ratio detector has been verified by an oscillographic study made of a typical set of this type.[19] An input signal of suitable level unmodulated in frequency but modulated in amplitude 50% was introduced, and the condition of this amplitude modulated wave as it progressed through the various tubes and circuits of the receiver explored at the mid-frequency of the band to which the receiver was tuned and at various other points within the band up to plus and minus 75 kilocycles.



Single stage diode limiter characteristic of circuit of Fig. 11.

Fig. 12

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[17] Jahrbuch der Drahtlosen Telegraphie und Telephonie, Bd. 54 (1939), Heft 2.

[18] The investigation was carried out at low frequency.

[19] R.C.A. Crestwood Type 612V1.

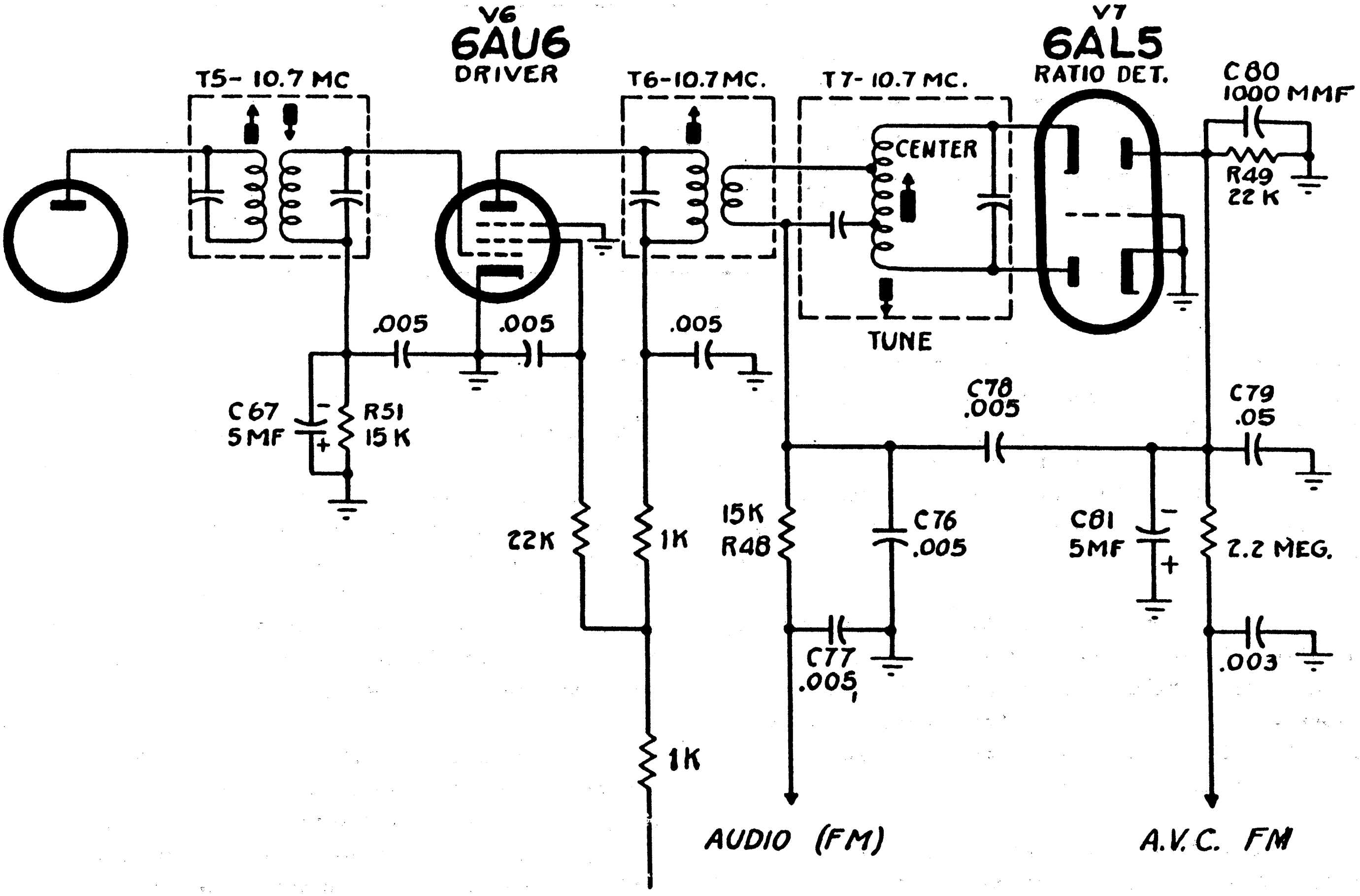

Fig. 13

Two methods of observation of the conditions existing within the circuits were employed. In one, the 10-megacycle IF currents and voltages were observed directly by means of a 10 megacycle oscilloscope. In the other, the exploration was made by means of a superheterodyne receiver arranged to beat the 10 megacycle intermediate frequencies down to values where they could be conveniently examined with the ordinary low frequency scope. In each instance the amount of energy abstracted from the circuit examined was held to a value sufficiently small so that the circuit characteristics remained unaltered by the sampling operation. Figure 13 illustrates the schematic arrangement of the circuits examined.

The arrangement of the "ratio detector" circuit of this receiver differed in some details from the arrangement described in RCA Laboratories Bulletin No. 645, but electrically the differences are not significant. The so-called "driver" tube circuits, however, contain a change which is significant. Instead of the usual biased amplifier connection, an unbiased grid circuit containing a large condenser and shunted resistance having a long time constant is employed. This arrangement serves to reduce the amplification to about one-third that obtainable with a biased amplifier. The purpose of sacrificing amplification in this way will appear from the following reproductions of oscillograms of the currents in the "driver" tube circuits. The essential elements of the ratio detector circuit of Figure 13 are redrawn in Figure 14 to clarify the diagrammatic portrayal of the circuit.

The method of investigation of what happens in the "driver" and detector circuits of the receiver of Figure 13 was carried out in the following way. The driver tube V6 had the large condenser C67 and resistance R51 replaced by a biasing battery of the proper value to give the same output. The cathode heater currents of the ratio detector tube V7 were cut off so that the resistance across the secondary circuit of the discriminator transformer became virtually infinite.

Under these conditions, with a 50% AM modulated signal applied to the grid of the driver tube the currents in the grid circuit and the plate cir-

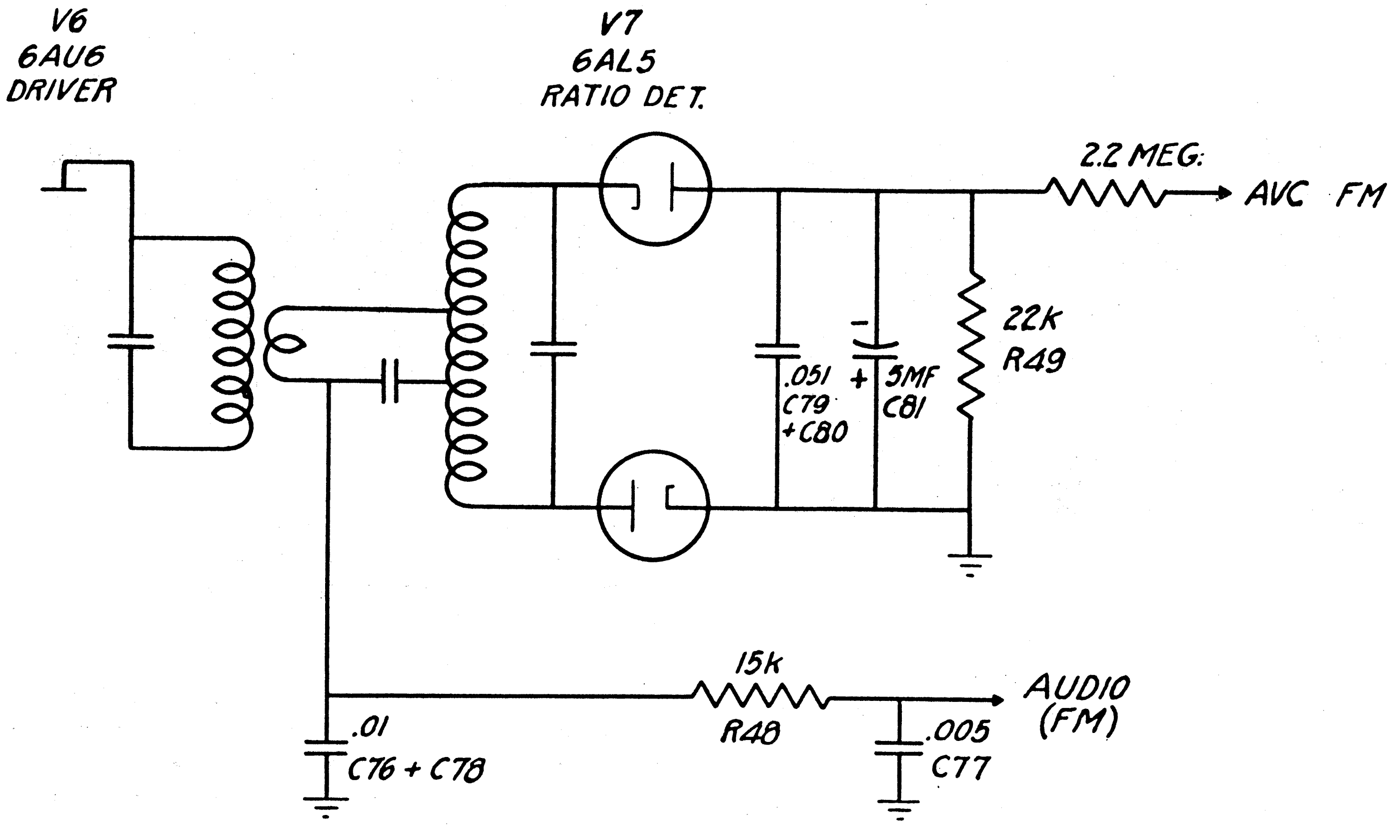

Fig. 14

cuit of V6 were investigated with a probe. The level was appropriate to give linear amplification in the driver tube, so it follows that a 50% amplitude modulated signal of the character shown, respectively, in Figures 14a, 14b and 14c was observed in the grid circuit, the plate circuit, and the secondary of the discriminator transformer.

Next, the biasing battery on the driver tube was removed and the normal grid circuit of the large condenser C67 and the resistance R51 was restored. The grid circuit of the driver tube now loads the tuned circuit to which it is connected, so that a reduction in amplification of about 3 to 1 takes place, which is accompanied with a reduc-

Wave form at grid of V6-6AU6 - "DRIVER" tube.
Signal generator - 50% modulation.
Grid return of this tube (V6) battery biased to produce approximately linear operation as an amplifier.

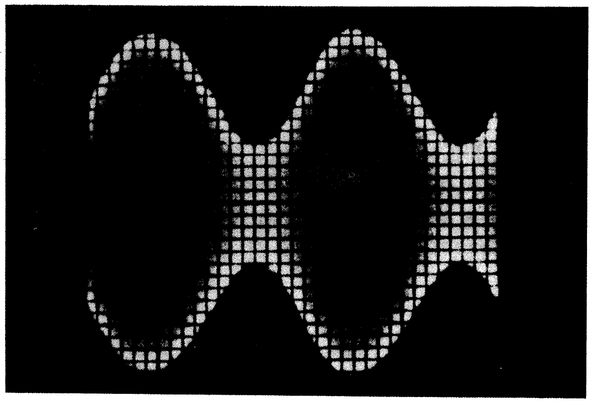

Fig. 14a

Wave form at plate of V6.
Signal generator - 50% modulation.
Grid return of V6 battery biased.

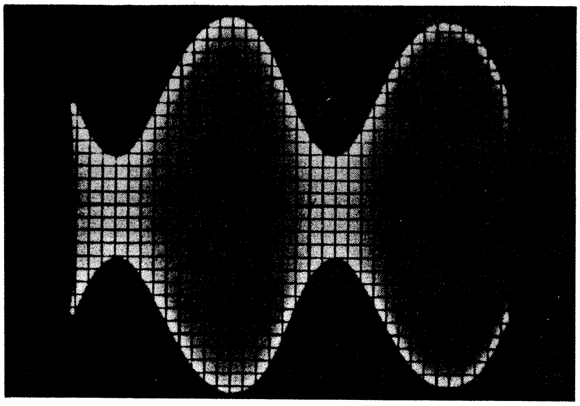

Fig. 14b

Wave form in discriminator secondary.
Signal generator - 50% modulation.
Grid return of V6 battery biased.
Heaters of V7 - off.

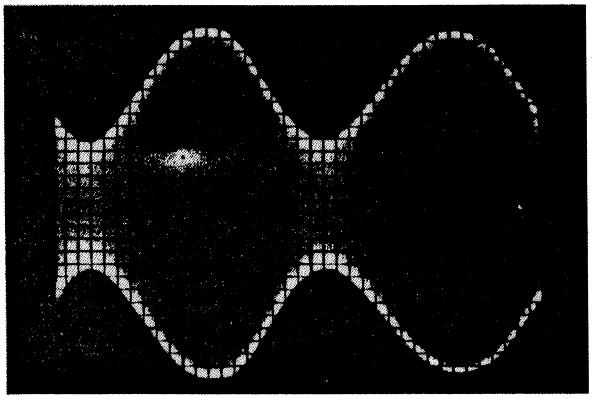

Fig. 14c

tion in the percentage of amplitude modulation because of the potential limiting of amplitude changes in the grid circuit by the RC combination in the grid.

Figure 15 now shows the wave form in the plate of tube V6 where an elimination of approximately half the amplitude modulation has taken place. A similar wave form is found in all the discriminator circuits, for the heater current has not yet been turned on. Next, the heater current was turned on and the diodes put into normal operation. Under these conditions the current in the secondary now becomes as illustrated in Figure 16, wherein the amplitude modulation is almost completely removed. This result, of course, is caused by the limiting action of the diodes on the secondary in the manner shown by Zuhrt.

Wave form in plate circuit of V6.
Signal generator - 50% modulation.
Grid return of V6 - normal.
Heaters of V7-6AL5 - "Ratio DET." off.

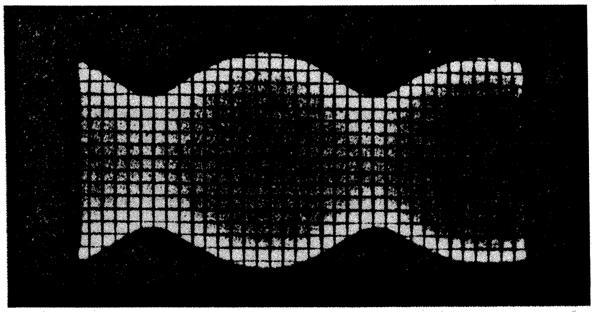

Fig. 15.

Wave form in discriminator secondary.
Signal generator - 50% modulation.
5 MF condenser (C81 and C79) in circuit, driver grid circuit normal.

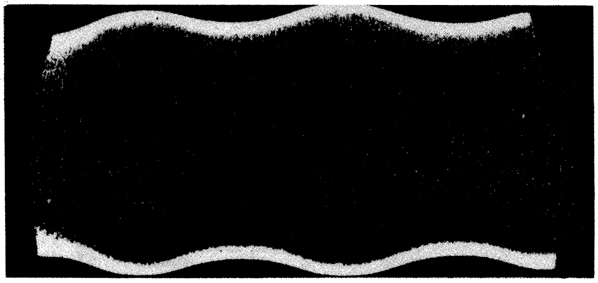

Fig. 16

The manner of operation of the ratio detector is now perfectly clear. When examined for the properties of a limiter it is found to have them. In other words, it has the inherent property of suppressing amplitude modulations. Similarly, when viewed as a discriminator-detector, it is found to function as such.

The fact that these two properties are combined into a single circuit configuration and are therefore inherent in its operation does not alter these facts. However, as in all devices which perform double functions, the choice between conflicting requirements of design must be a compromise, and depending upon the choice made by the designer, various degrees of effectiveness of the limiting function may be expected.

The experimental part of this investigation, reported in the paper and in Appendix One attached hereto, has been carried out by Messrs. John Bose and Glenn Musselman, to whom the full credit is due. The work, extending over a period of many months, has produced a large amount of additional information not appropriate to the immediate paper. Further measurements will be made public in due course.

APPENDIX ONE

There are, of course, all degrees of effectiveness of the removal of amplitude modulation in the various arrangements of these self-limiting circuits. A method of examination which may be conveniently used for comparing the steady state operation of the different arrangements is described herewith.

As a standard of reference a Zenith Model 7H822 was employed, with its limiter tube modified to act as a straight amplifier. With this arrangement the audio output voltage was measured for a 50% amplitude modulation on a fixed frequency carrier at the balance point and at various points throughout the band. With the amplitude modulation removed and a frequency deviation of 75 KC the FM audio output was obtained as a standard of reference. This enabled a ratio of E_{fm} to E_{am} voltage to be obtained for various points within the band. A similar set of readings was obtained for a type RCA 68R3 ratio detector set with the electrolytic condenser removed from the circuit so that the self-limiting action did not take place.

Figure 17 illustrates the readings obtained at voltages corresponding to an input level of 100 microvolts. It will be observed that the ratios obtained with the voltage balance type of discriminator as used in the Zenith set, and those obtained with the current balance type employed in the RCA set, were substantially the same.

RATIO OF E_{FM} / E_{AM} (NO LIMITING)
RCA MODEL No. 68R3 and ZENITH MODEL No. 7H822

f	E_{fm} / E_{am} R.C.A.	E_{fm} / E_{am} Zenith
+ 75	1.78	1.9
60	2.27	2.2
37	3.33	3.2
20	6.25	5.4
0	83.33	72.2
20	6.25	6.0
37	3.12	2.7
60	2.08	1.6
- 75	1.56	1.2

Fig. 17

In order to make the ratio detector measurements it was necessary to remove the ground from one end of the load resistor and center-tap that resistor to ground. This, however, produces no change in the operation of the device.

RATIO OF IMPROVEMENT DUE TO LIMITING,
RCA MODEL No. 68R3

f	E_{fm} / E_{am} Without Limiting	E_{fm} / E_{am} With Limiting	Improvement Ratio Due To Limiting
+ 75	1.78	27.7	15.5
60	2.27	27.7	12.2
37	3.33	27.7	8.3
20	6.25	31.2	5.0
0	83.33	41.6	.5
20	6.25	31.2	5.0
37	3.12	20.8	6.6
60	2.08	16.6	8.0
- 75	1.56	17.8	11.6

Fig. 18

After these ratios had been obtained, the function of limiting was restored to the two sets and a similar set of ratios determined for each. Figure 18 illustrates the improvement in the ratio of E_{fm} / E_{am} which takes place when the large condenser is connected across the load to produce self-limiting. The effect is most pronounced at the extremes of the band, where the greatest unbalance for the non-limiting condition occurs. Hence, the ratio of E_{fm} / E_{am} at + 75 KC of 1.78 without limiting improves to 27.7 with limiting, or a matter of fifteen and a half times; and at - 75 KC the ratio of 1.56 becomes 17.8, or an improvement of eleven and six-tenths times in the reduction of amplitude variations. As these are voltage ratios, the reduction in the noise level on an energy basis at these points is over one hundred-fold at one end of the band, and over two hundred-fold at the other end. The improvement decreases as the center of the band is approached. At the exact center the ratio reverses and is somewhat less for the case with the limiter, as a more accurate amplitude balance appears to be obtainable without it.

There are a variety of types of connections for self-limiting circuits, and no attempt will be made to analyze them all. Figure 19, however, illustrates a series of E_{fm} / E_{am} ratios for a number of receivers now on the commercial market. These figures are not intended to be illustrative of the individual performance of the different sets, as such comparison would require examination of a number of samples of each make and a determination of the figure of merit for various input levels. The figures are, however, designed to give a rough idea of the performance of the various sets under the conditions of the test.

RATIO OF IMPROVEMENT DUE TO LIMITING,
OF SOME COMMERCIAL TYPES OF F.M. RECEIVERS

f	Zenith 7H822	R.C.A. 68R3	R.C.A. 8R71	Philco 48-475
+ 75	14.6	15	2.8	22
60	14.8	12	2.8	23
37	13.5	8	2.6	20
20	14.0	5	2.4	13
0	.8	0.5	0.5	0.5
20	16.6	6	4.0	10
37	16.6	7	4.0	17
60	15.2	8	4.5	27
- 75	15.0	12	5.0	29

Fig. 19

It should be noted that the ratios measured are steady-state ratios and are not representative of what happens under conditions of ignition interference or of improper I.F. band characteristics, as the performance of the ratio detector deteriorates rapidly under such conditions.

In these measurements the operational characteristics of the detection systems were isolated from the effects of faulty line-up of IF transformers by determining the voltage produced on the grid of the limiter or of the driver tube for an input signal of 100 microvolts (300 ohms in series with the signal generator) at the mid-frequency. Corresponding IF voltages were then applied to the grids of the limiter and driver tubes at the proper intermediate frequency.

APPENDIX THREE

During the presentation of the paper a visual and aural demonstration of the removal of amplitude variations by the ratio detector circuit was conducted, using the arrangement of Figure 20. The receiver employed in the demonstration was the R.C.A. "Crestwood", Type 612-V1, to which reference has heretofore been made.

Conditions existing in the secondary circuit of the arrangement of Fig. 20 were examined by obtaining a sample of the current flowing in it with a single turn coil around the discriminator secondary. This coil could be switched to a 10-megacycle scope or to a crystal rectifier - amplifier - speaker system for indicating aurally the noise levels.

Two sets of demonstrations were made. The first showed the effect of the 15,000 ohm resistance and 5-microfarad condenser combination in reducing amplitude variations in the driver tube circuit. This was illustrated by the picture seen in the scope under the following conditions______;

The heater current of the ratio detector tube V7 was cut off so as to remove all limiting action from the circuit by that tube. A 50% amplitude modulated signal at mid I.F. frequency was fed into the I.F. system and so applied to the driver tube, and the voltage obtained from the biasing source indicated at B was adjusted to give the same amplification with S1 to the left with the fixed bias, as when S1 was thrown to the right and a self bias furnished by the resistance-capacity combination.

Observation of the current in the secondary of the discriminator by means of the scope showed that the 50% modulation which appeared in the secondary circuit when the separate bias was used dropped to less than half of that when the resistance-capacity combination was cut into the grid circuit of the driver tube.

The second step in this demonstration was carried out with the heater currents in the ratio detector tube switched on and with the switch S2 closed to restore the normal ratio detector circuit. Under these conditions the amplitude modulation as indicated by the scope was reduced to a very small fraction of carrier level.

In this test the automatic volume control was cut out so that constant level at the input of the driver tube was maintained.

The second demonstration was arranged to show, aurally, the limiting action of the ratio detector tubes on thermal or tube noise in the secondary circuit of the discriminator. With the full receiver in operation and switch S1 on the separate bias the sampling loop was connected to the crystal rectifier - audio amplifier - speaker system, so that an audible response to the currents in the secondary circuit resulting from thermal and tube noise was produced.

An R.F. carrier was introduced at the input terminals of the receiver and adjusted in level so that with switch S2 open the noise level could be clearly heard throughout the room. The closing of the switch S2 put into operation the limiting action of the diodes, and the noise dropped to a small fraction of that obtained when S2 was open. The reading of a direct current meter in series with the crystal rectifier stayed constant, regardless of whether switch S2 was opened or closed, indicating that the level of the R.F. current in the secondary circuit had not changed and that the decrease in the noise from the speaker was due entirely to the elimination of amplitude variations in the secondary current. In this test, likewise, the A.V.C. circuit was cut out, although the D.C. voltage measured across R49 indicated no change when the 5 mfd condenser was cut in and out.

The elimination of the noise modulation on the secondary current with the closing of switch S2 could also be observed visually on the scope.

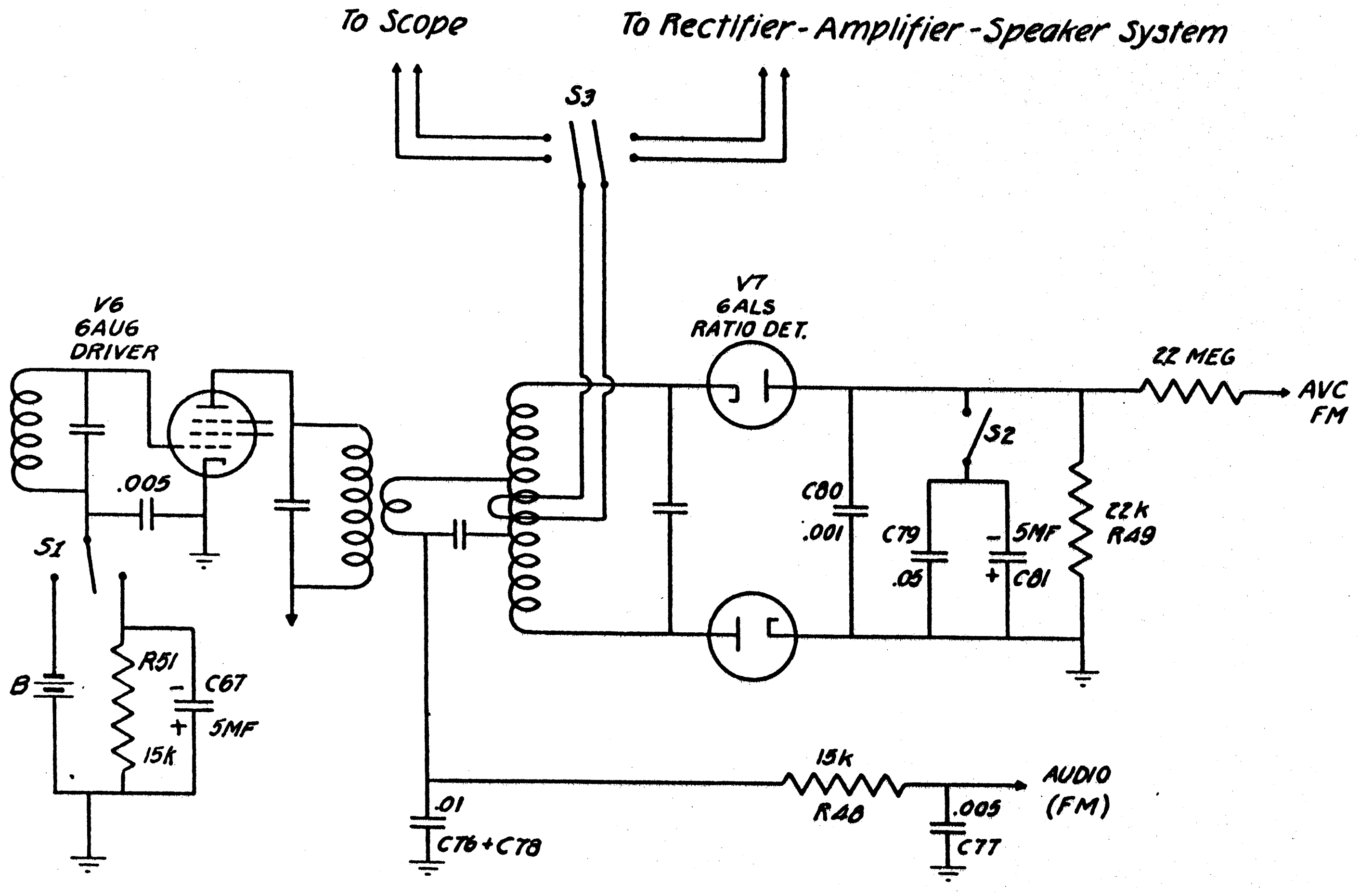

Fig. 20

APPENDIX FOUR

During the presentation of the paper, reference was made by the writer to two documents which may have an effect in radio history similar to that which the lost order of General Robert E. Lee, Commander of the Army of Northern Virginia, had on the fortunes of the Confederacy during the invasion of the North in the Summer of 1862.[1]

The first document was a "Report on the RCA Ratio Detector" written by the head of the Patent Department of the Philco Corporation and embodied in an exhibit in a securities registration statement filed with the Securities and Exchange Commission (at Philadelphia,Pa.)[2] Excerpts from the report were read which confirm the analysis of the paper.

A second document, written by the head of the FM Section of the Patent Department of the Radio Corporation of America, was likewise referred to, and excerpts from that document defining the nature of the wide swing invention were likewise read.

The character of these documents and their relation to the public interest is such that the writer felt the situation justified some special comment. Recalling how some thirteen years ago, when he had last appeared before the Radio Club on the occasion of the presentation of the original FM paper, he had predicted the day was in sight in broadcasting when the noise of the thunder coming in the window would be more disturbing to the radio listener than the effect of the lightning on his radio set, and that that prophecy had now come to pass in the areas served by the 673 FM stations now on the air, he stated that the time had arrived to venture another prophecy.

That prophecy was that the day would surely arrive when the direction of engineering by the members of the legal profession would come to an end, because the unholy mess that they had made of radio would soon be apparent to everyone. The writer predicted that engineering would again be directed by engineers, and he even ventured to think that the day might arrive when some highly successful executives would come to believe that there was something after all to the text of the Eighth and Ninth Commandments,[3] stating that in case the audience could not immediately place them by number that they were "Thou shalt not bear false witness against thy neighbor" and "Thou shalt not steal".

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[1] The lost order of General Lee to Major General D.H. Hill which fell into the hands of General McClellan, Commander of the Army of the Potomac, disclosed the disposition of General Lee's forces and enabled the Union Commander to fight the Battle of Antietem (Sharpsburg) under circumstances so unfavorable to the Army of Northern Virginia as to compel its retirement across the Potomac River into Southern territory. For the best accounts of the story of the lost order and its subsequent effect, see: "Lee's Lieutenants", Volume 2, by Douglas Freeman, and "Robert E. Lee", Volume 2, by the same author. Also "Battles and Leaders of the Civil War", a compilation of articles written by leading participants on the Union and Confederate sides.

[2] Exhibit 17-L, File No. 2-6525, filed June 20, 1946 with Securities and Exchange Commission, Philadelphia,Pa.

[3] (Protestants numbering, generally)

Volume 30 1953 No. 3

SOME RECENT DEVELOPMENTS IN THE MULTIPLEXED TRANSMISSION OF FREQUENCY MODULATED BROADCAST SIGNALS

by

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JOHN H. BOSE*

Presented before Radio Club of America on October 13, 1953

It is the purpose of this paper to describe some recent developments in multiplex signaling in the F.M. broadcasting field, with special reference to the experimental work that has been carried out in broadcast transmission and reception from Station KE2XCC[1] at Alpine, New Jersey. The transmissions from Alpine to which this paper is specifically directed began in April, 1948. The development of the equipment which is employed began with the termination of hostilities in World War II and was carried out at the Marcellus Hartley Research Laboratory at Columbia University.

HISTORICAL:

The subject of "multiplexing" in radio signaling is an old one, dating back, in fact, to the days of Marconi's "syntonic" radio signaling experiments in the year 1900 with spark transmitters. The term was originally applied to the simultaneous transmissions of two or more spark transmitters (the only workable transmitter of the day) through a single antenna system and their simultaneous reception via a single receiving antenna. Selection between the transmissions was limited to the capabilities of the radio frequency circuits of the time. Subsequently, the idea of time division between several transmitters and receivers was advanced.[2] It was proposed to progressively connect each transmitter and its corresponding receiver to their respective antennas for short intervals by mechanical switching arrangements operated synchronously with each other, a crude concept of some present pulse communication techniques. Still later,[3] it was proposed to transmit signals of different audible frequencies on a single wave length, and to separate them on the basis of tone selection circuits. Nothing practical resulted from this proposal.

The first concept of "frequency division" multiplexing, in the form of superaudible subcarrier modulation appears to have been due to R.A. Heising.[4] The system proposed was that of amplitude modulation of a carrier with appropriately spaced superaudible frequencies, which were, in themselves, amplitude modulated by the signals to be transmitted. While of effect for wire line signaling, the ravages of noise and fading appear to have prevented its use in the radio field.

The practical art of multiplexing in radio signaling, we believe, begins with the advent of the wide band system of frequency modulation in 1934. In November of that year, four different sets of signals were successfully transmitted from Station W2XDG located in the Empire State Building, New York City, to Haddonfield, New Jersey, a distance of 85 miles,[5] (41 megacycles). The signals transmitted on that occasion were a musical program on the main channel, a facsimile program on a superaudible subcarrier on a second channel, a synchronizing signal for the facsimile on a third, and a telegraph "order" channel on a fourth subcarrier frequency. Amplitude modulated subcarriers were employed in this instance. Subsequently, two musical programs (the Red and Blue programs of the NBC Network)[6] were simultaneously transmitted, using the same system of subcarrier modulation and still subsequently, (April, 1935) the amplitude modulated subcarrier was replaced by a frequency modulated subcarrier and the same two network programs transmitted with substantially improved results.[7]

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* Marcellus Hartley Research Laboratory, Columbia University.

[1] Formerly designated W2XMN.

[2] Wireless Telegraphy and Telephony - Mazzotta (1906) p. 329 Cohen-Cole System.

[3] Wireless Telegraphy and Telephony - Maver (1910) p. 118 Telefunken.

[4] Radio Telephony - Craft and Colpitts, Transactions A.I.E.E. February, 1919.

[5] "A Method of Reducing the Effects of Disturbances in Radio Signaling by a System of Frequency Modulation" by E.H. Armstrong, Proceedings I.R.E., May 1936.

[6] Cited supra.

These transmissions, while successful according to the standards of the times, would hardly measure up, either to the signal-to-noise ratio, or the quality of reproduction that are now the accepted standard of F.M. broadcasting. Nor would the receiving equipment designed to operate in that ideally untrammeled wilderness of the wide open spectrum spaces of 1934, when there was in existence one wide band transmitter and one receiver only, perform too satisfactorily in the presently well-settled FM territories where in many locations, signals on a score or more different channels may be picked up in a sweep across the dial of an appropriately sensitive and selective receiver.

THE SYSTEM PROBLEM

The problem that immediately confronts us in introducing a workable multiplex system is that of superimposing extra channels on a going broadcasting business which is fitted into an existing and not easily changed governmental allocation pattern - and doing this without affecting the quality of the transmitted wave and without creating disturbances in the receivers that are presently in use. General considerations indicate that a subcarrier frequency of the order of 30 kilocycles which is itself frequency modulated is a suitable compromise for the factors involved. Practical operation with this standard at KE2XCC where the subcarrier is now 27.5 KC has confirmed this. No instance has yet been reported of disturbances to existing receivers, nor have repeated tests with the standard make receivers shown any detectable effect on the main channel. The part of the problem which consists in the superposition of an auxiliary carrier without affecting the transmission on the main channel is not a difficult one, particularly when the modulation on the subcarrier is sinusoidal in character.

The corollary problem, that of keeping the effects of the main channel out of the auxiliary channels is not however, equally simple. This is the real problem in F.M. multiplex broadcast operations. It arises from cross-modulation in both the transmitter and the receiver.

THE TRANSMITTER PROBLEM:

The effect of cross modulation in transmitters is much more severe in high quality broadcasting than it is in communication circuits, where the criterion is primarily that of the transmission of intelligence. In broadcasting where the transmission is basically for entertainment, more difficult requirements must be met, particularly during the transmission of a separate program on a second channel when a diminuendo or a period of silence of that channel corresponds with a crescendo on the main channel. Experience indicates that cross talk above the level of the background noise of the second channel is objectionable, so that the energy content of the cross modulation with respect to signal level must be held to -50 decibels or less, or an energy content of the order of one one hundred thousandth part of the program level of the second channel. A ratio of 60 db or one part in a million is an attainable goal.[8]

Since the auxiliary channel lies in the 20 to 40 kilocycle band and since the second and third harmonics of the upper half of the main channel modulation fall within that band, it will be clear that the transmitter problem will not yield readily to a solution by any direct method of modulation, for the "free oscillator" type of circuit does not lend itself to the required low distortion level.

Present day practice in FM broadcast transmission indicates that the phase shift method of producing frequency modulation is destined, in the absence of some new discovery, to be the surviving method of modulation. The reasons for this are now well known to everyone. This result became inevitable with the invention by J.R. Day of the Serrasoid[9] type of modulator (which made use of an idea originally advanced by R.D. Kell)[10] that solved completely, for simplex signaling, the one remaining problem of the phase shift method of producing frequency modulation i.e. residual modulator noise.

It is in order here to refer briefly to the nature of the transmitter background noise difficulty. All phase shift modulators have had to contend with it, and it comes about basically because the limited initial frequency change that can be obtained in a phase shift modulator entails a high degree of frequency multiplication to produce the ultimately required deviation of the transmitted wave. This high order of multiplication has the effect of enhancing those noise frequency modulations that result from the interaction of thermal and tube noise currents with the basic carrier in the oscillator and modulator circuits; hence, an appreciable background hiss level was characteristic of the early phase shift modulators. The noise level of the early modulators (-65 db) was reduced to values that were relatively unimportant for simplex signaling by the invention of the double channel modulator, i.e., to better than -70 db, and with the invention of the Serrasoid to -80 db, a value which may be taken as giving a complete solution for simplex operation.

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[7] Cited supra.

[8] The measure of the cross talk of the first into the second channel is obtained by modulating the first channel at the frequency which produces maximum cross talk in the second when that channel is unmodulated. A deviation of plus and minus 75 KC in the first channel is employed and the cross talk ratio is expressed in terms of the measured value of disturbance in the second channel below the output for full modulation of the second channel.

[9] The Serrasoid F.M. Modulator, Proceedings Radio Club of America, Vol. 26, No. 1 (1949).

[10] U.S. Patent 2,280,707-R.D. Kell.

In multiplex signaling in the broadcast service, however, when an attempt is made to increase the frequency range of modulation, then, even with the Serrasoid modulator, the difficulty again manifests itself. This result comes about because the fluctuation current components lying 20 to 40 kilocycles distant from the oscillator frequency produce correspondingly enhanced frequency deviations within the range of subcarrier channels, and these deviations, after being enhanced by the same amount of frequency multiplication that is required for a 30 cycle modulating frequency, produce a level of background noise in auxiliary channels that is not acceptable. A second difficulty incident to introducing subcarrier modulation on phase shift modulators lies in the cross modulation introduced in the multiplier chain because of the selectivity characteristics required of the multiplier coupling impedances. It is essential that the lower frequency stages be sufficiently selective to eliminate the frequency modulation superimposed on the transmitted frequency at the basic oscillator frequency, a phenomenon that has its origin in the initial multiplier stages. Hence, the selectivity that is needed in the inter-multiplier coupling stages to remove this frequency modulation results in a lack of linearity in the phase characteristic for frequencies required to carry the subcarrier and so gives rise to cross modulation in those stages.

A solution for this difficulty has been found by the segregation of the modulation functions in the manner indicated in Fig. 1, where the modulation and the initial multiplications of the main

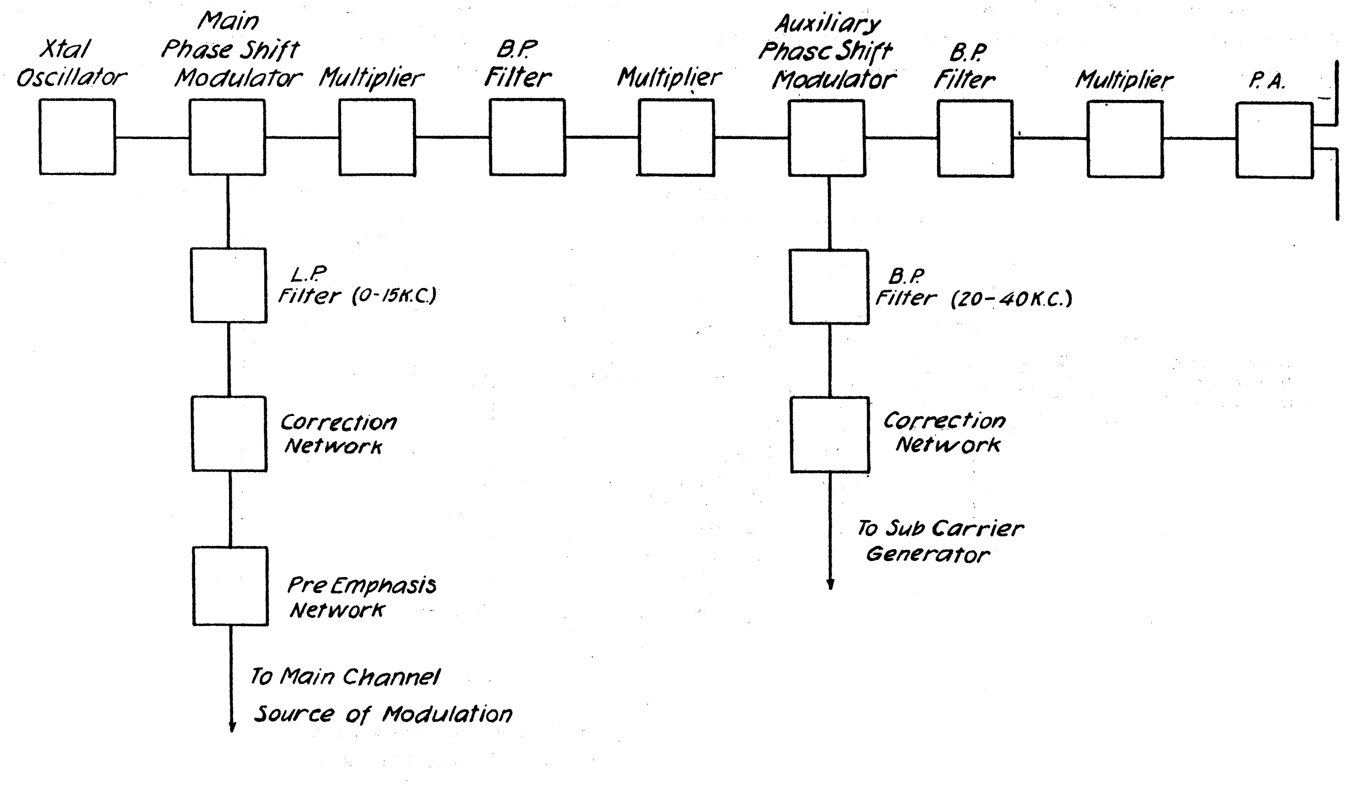


Fig. 1

channel are carried out (with certain modifications) as in simplex operation, and the modulation of the auxiliary channel is super-imposed at a point in the multiplication chain where relatively few additional stages are required to obtain the necessary subcarrier swing at the radiated frequency. An appropriate point for introducing the auxiliary modulation is around the 2 to 3 megacycle frequency range where the amount of phase shift necessary at the subcarrier frequency to produce the required ultimate change in frequency of the radiated wave is of the order of 1° in contrast to that necessary at the modulator for the main channel where approximately 150° phase shift (plus and minus) is employed to obtain the full deviation range for the low end of the modulation current band (30 cycles). As a consequence of this, no linearity problem results from the operation of two phase shift modulators in cascade. A phase shift modulator such as illustrated in Fig. 2 may be employed. The cross-modulation problem in the multiplier coupling stages is avoided because it is possible to make the coupling circuits of the last few multiplication stages quite broad. This can be done as the frequency modulations imposed on the transmitted carrier by the basic oscillator frequency and by the fluctuation disturbances lying in the subcarrier frequency range are no longer a problem at this point. The noise difficulties attendant to operating a wide range modulation frequency system have been avoided by the narrowing down of the band width of the early multiplication stages of the main channel, so that the frequency changes introduced by thermal and tube noise component currents lying more than plus and minus 15 kilocycles from the oscillator frequency are not passed on into the auxiliary channel. The cross modulation problem has been avoided by keeping the two channels separated until the normal circuit bandwidth requirements permit the use of circuits sufficiently wide to insure the necessary phase linearity to prevent the effect.

The principle of the system may likewise be carried out in the manner indicated in Fig. 3 or in some similar combination, although in general, the arrangement of Fig. 1 is preferable. It has been found that with plus and minus 75 kilocycles deviation on the main channel and plus and minus 20 kilocycles deviation on the auxiliary channel, the cross modulation into the second channel for full modulation on the main channel by the most troublesome frequencies can be held in the transmitter to better than -60 decibels. We believe this figure can be lowered.

Although there are a number of ways in which the auxiliary carrier modulating current can be produced, we have adopted at the Alpine transmitter the method illustrated in Fig. 4, making use of a Serrasoid modulator of standard design, which multiplies the frequency up to 10 to 12 megacycles and heterodynes this frequency down to the subcarrier frequency of 27½ K.C., by means of an

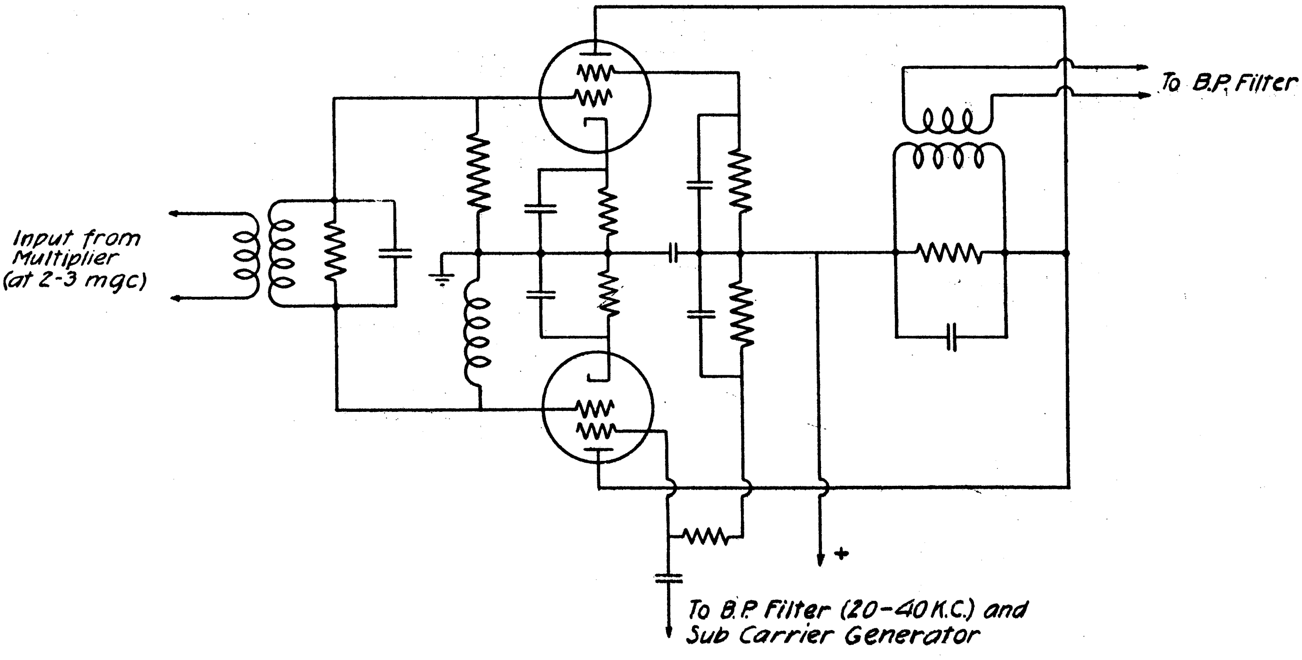


Fig. 2

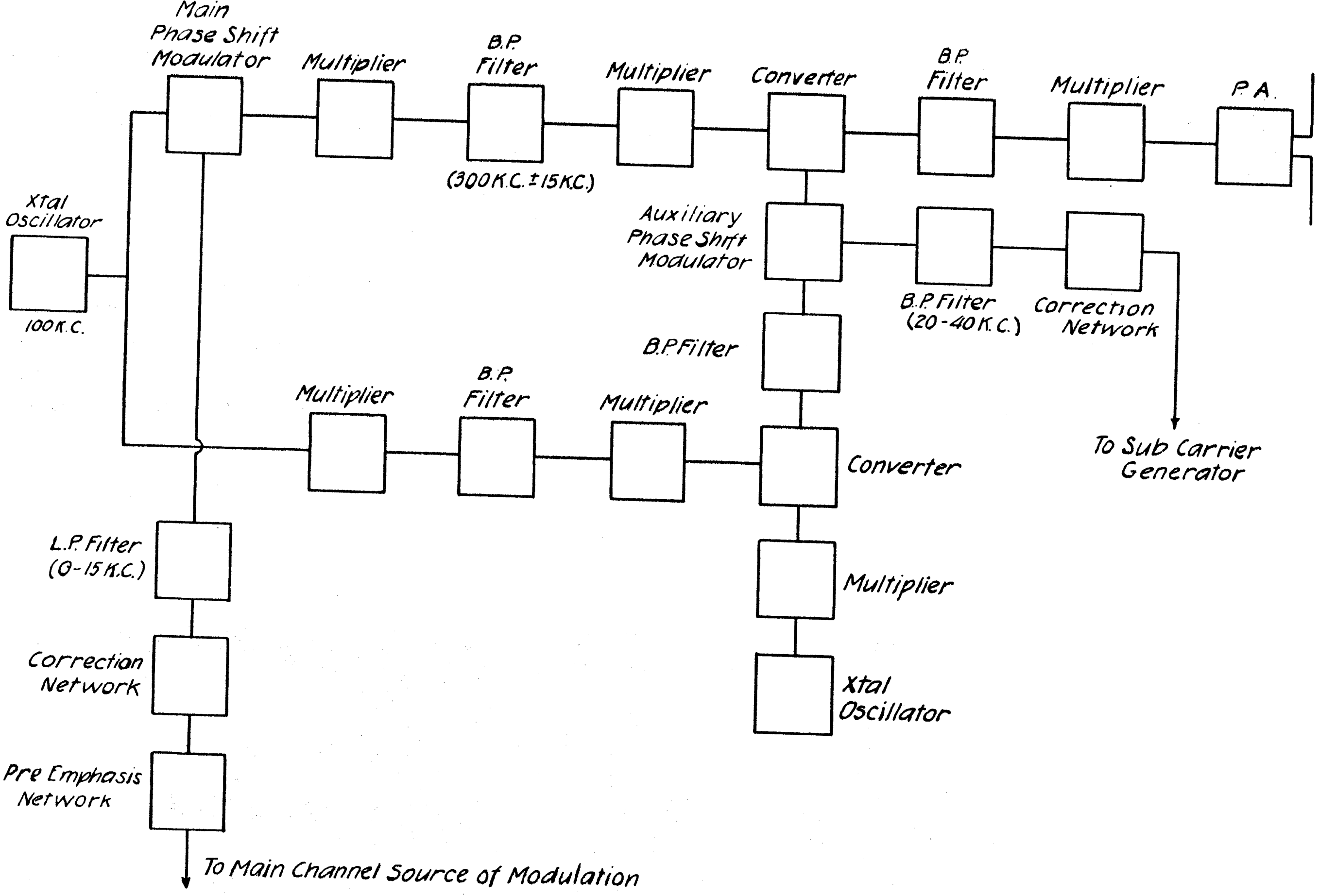

Main Phase Shift Modulator
Multiplier
B.P. Filter
Multiplier
Converter
B.P. Filter
Multiplier
P.A.
(300 K.C. ± 15 K.C.)
Xtal Oscillator
100 K.C.
Auxiliary Phase Shift Modulator
B.P. Filter (20-40 K.C.)
Correction Network
B.P. Filter
Multiplier
B.P. Filter
Multiplier
Converter
To Sub Carrier Generator
L.P. Filter (0-15 K.C.)
Multiplier
Correction Network
Xtal Oscillator
Pre Emphasis Network
To Main Channel Source of Modulation

Fig. 3

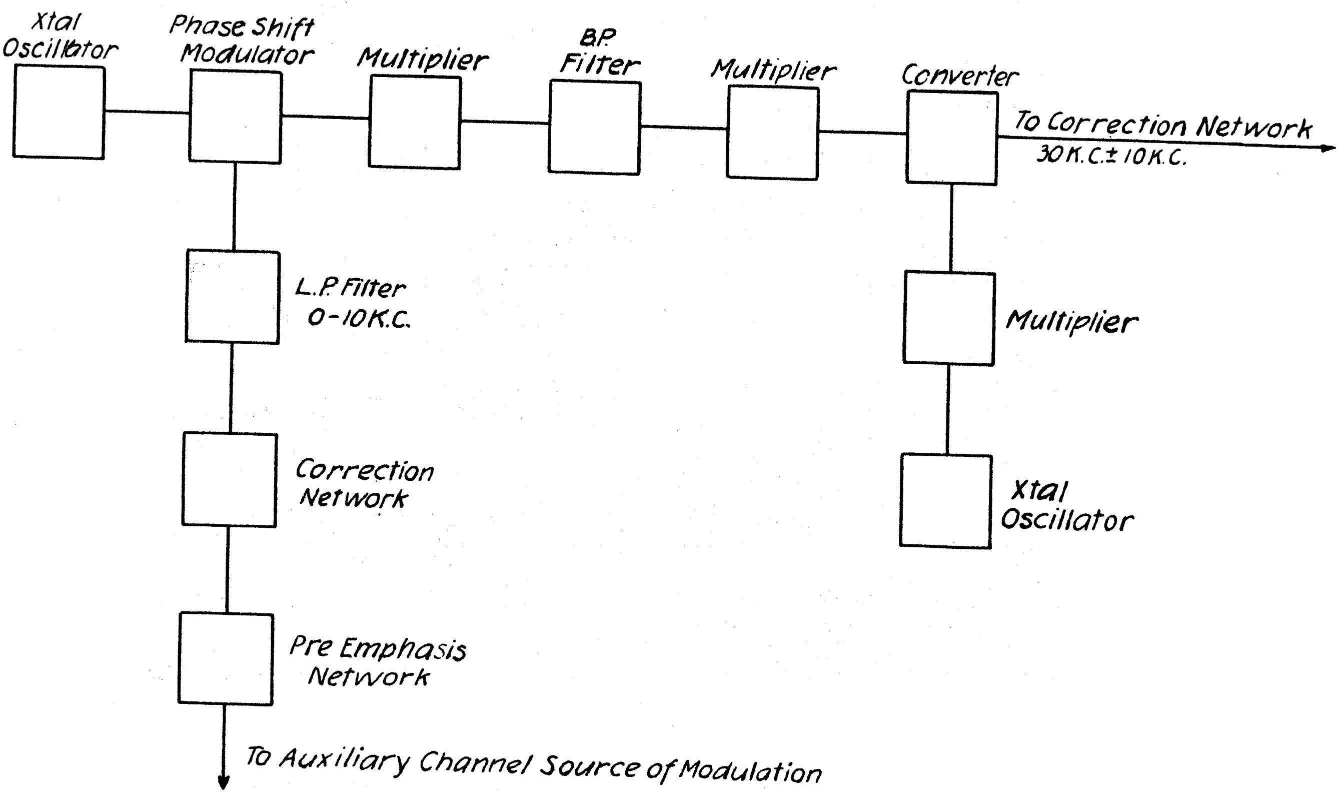

Xtal Oscillator
Phase Shift Modulator
Multiplier
B.P. Filter
Multiplier
Converter
To Correction Network
30 K.C. ± 10 K.C.
L.P. Filter 0-10 K.C.
Multiplier
Correction Network
Xtal Oscillator
Pre Emphasis Network
To Auxiliary Channel Source of Modulation

Fig. 4

appropriate crystal controlled oscillator. The output current is then passed thru a correction network and a band pass filter to the auxiliary modulator. The usual pre-emphasis circuits are employed in the modulation applied to the Serrasoid modulator. In practice, this method of obtaining the subcarrier channel has proven stable and reliable and while somewhat more apparatus is required than for other ways of obtaining the result, it is doubtful if their reliability or performance can equal that of the method presently in use. Fig. 5 shows the multiplex installation at Alpine. The rack at the extreme left on which Mr. Osborn's hand rests contains the auxiliary channel generator together with the auxiliary modulator.

THE RECEIVER PROBLEM:

In the absence of the overloading of the initial stages of a receiver, the principal sources of cross modulation lie in the intermediate frequency selective means and in the first discriminator of the receiver. The intermediate frequency

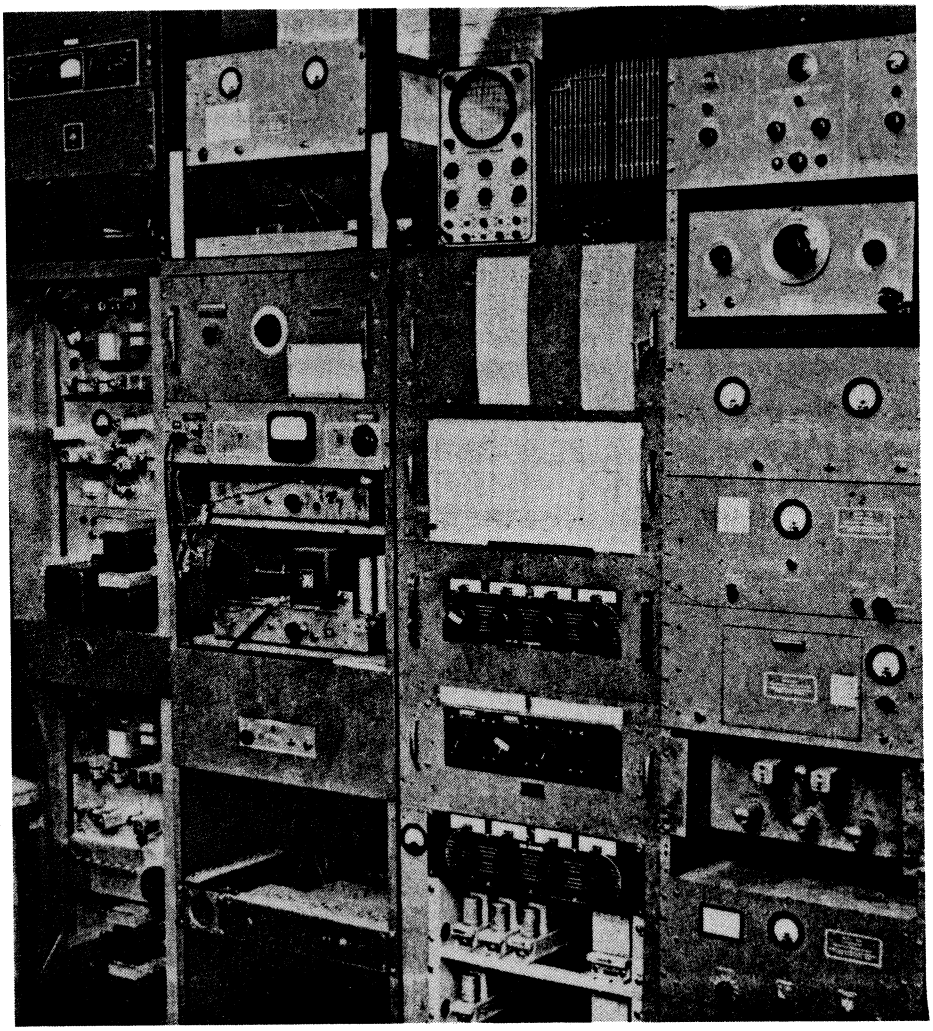


Fig. 5. CONTROL ROOM AT ALPINE -- Main and auxiliary modulation equipment contained in rack on extreme left with Mr. Perry Osborn, Chief Engineer, KE2XCC beside it.

selectivity will not be a problem in metropolitan areas where the signal to be received is substantially stronger than adjacent channel interference, but can become so on the fringe of reception where the adjacent channel signal level is commensurate with, or may be in fact, stronger than that of the channel to be received. With the licensed service area of F.M. transmitters located on the Eastern seaboard limited to a level of 1 millivolt field (at 30 ft) however, it is not anticipated that serious difficulties will be found. The problem of cross modulation in the discriminator, however, will be present at all locations, and must be guarded against, as it is the most pernicious source of all cross modulation effects. Low conversion ratios are mandatory to secure the necessary freedom from them. A second point of vulnerability lies in the limiting and detection system of the second channel which must be well protected by a high pass filter from the effects of the main channel modulation. The general arrangement of the receiving equipment used in the field tests hereinafter referred to is illustrated in Fig. 6. This comprises a R.F. stage of amplification, converter, crystal controlled oscillator, 5 stages of 10.7 mgc. amplification, a double limiting system and a phase shift discriminator detector system. 13 tubes in the main channel receiver are employed: no attempt has been made to design for other than maximum effectiveness for experimental use.

The auxiliary channel section of the receiver comprises a 15 kc. high pass filter, resistance coupled amplifier, a band pass filter, and a frequency sensitive network, driving, thru limiters, a detector tube which may conveniently be of the 6BN6 variety. The total number of tubes involved are 6 without the audio amplifier. A 10 kc. low pass filter is presently provided for preventing overload of the audio amplifying system of the second channel by the subcarrier frequency but this is determined by the choice of 8 kc for the modulating band of the second channel. The general arrangement of this channel is illustrated in Fig. 7. Here likewise the design has been along the lines of maximum flexibility for experimental use. Subcarrier receivers requiring four tubes have been designed and built, which, while not affording the ultimate performance of the six tube type described will, nevertheless, give suitable performance for home use. Fig. 8 shows an auxiliary channel panel of the type used in the field tests above mentioned.

The characteristics of the two channels that are in use at Alpine at the present time are as follows: The main channel is modulated by a frequency band of 30 to 15,000 cycles with a maximum deviation which it is endeavored to maintain at about 50 kc. The deviation of the second channel is of the order of plus and minus 20 kc with a frequency deviation of the modulation on the subcarrier of plus and minus 5 kc. The maximum modulation frequency for the second channel is 7.5 kc. The usual pre-emphasis standards are used on all channels. Counter or phase shift type detection may be used on the subcarrier frequencies.

FIELD TESTS

The method of modulation herein described was installed at Alpine in 1948, and has been used for conducting a series of tests comprising facsimile, binaural and two audio program transmission. The

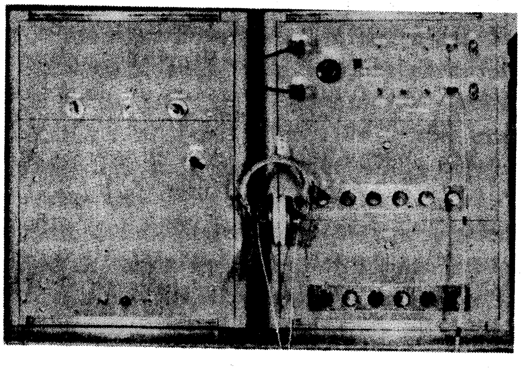


Fig. 6 (a)

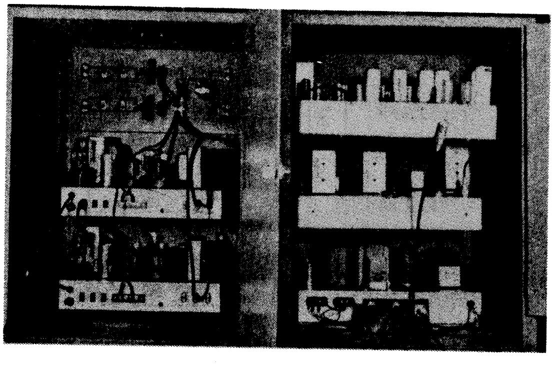


Fig. 6 (b)

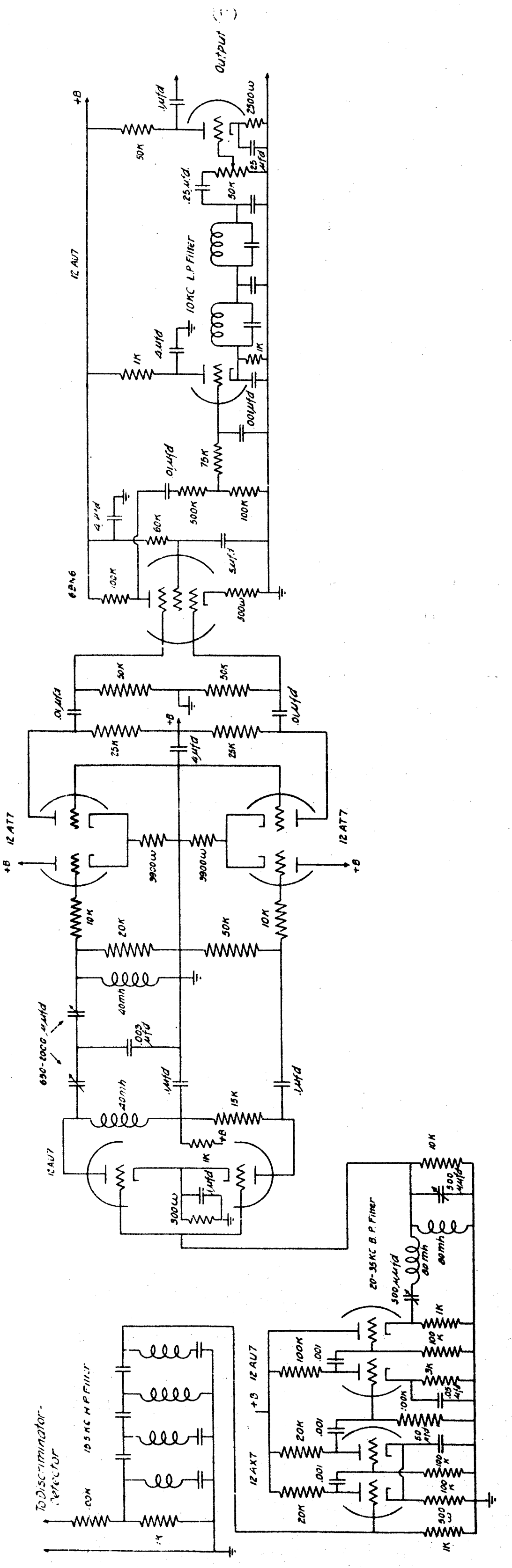
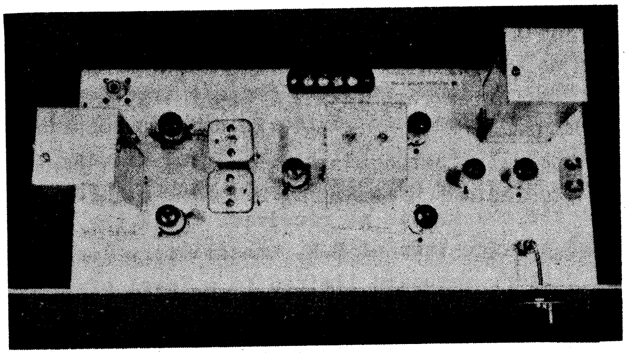


Fig. 7



performance of the multiplex channel has been perfectly stable; adjustments are permanent, and the operation is carried on with no more attention than that attendant to the operation of the main channel. The relative signal-to-noise ratios for the particular conditions chosen for the two channels differ by 10 to 20 decibels depending on the signal input level. The difference decreases at the higher signal level as the determination of the signal-to-noise ratio shifts from receiver noise as the governing factor at low levels to transmitter noise which governs at the higher levels. At the 1 millivolt line, the signal-to-noise level of the second channel for fluctuation noise is above 60 db with a single dipole antenna at the designated 30 foot elevation. Higher signal-to-noise ratios can be obtained at this line by the use of directional receiving arrays, and 70 db. is an attainable goal with arrays of practical dimensions.

The signal level required to produce an acceptable signal-to-noise ratio depends on the type of modulation on the second channel and of course, on the judgment of the listener. The order of vulnerability to noise and cross-modulation is highest for separate musical program transmission on the two channels, next in order is binaural transmission, with facsimile and printer operation and the like least affected. It has been found possible where receiver noise is the limiting factor to obtain intelligible transmission on the second channel at a signal level of 10 microvolts across the receiver[11]. To obtain a service superior to AM broadcasting (50 decibels) 100 microvolts across the receiver input is required. A 70 decibels signal-to-noise ratio (50 ohm input) can be attained at 1 millivolt across the terminals provided the transmitter residual noise is kept below this level.

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[11] 50 ohm input.

As a practical matter, the ability to transmit voice intelligence at a signal level of 10 microvolts across the receiver means that with Yagi antennas of a type readily available, the system is operable for the transmission of intelligence at a field strength of less than 10 microvolts per meter. These figures are given as the result of measurements on 2 receivers of the type illustrated here and indicate the field strength range over which the system may be effectively applied. Further tests are in progress at the present time which will be reported subsequently.

During the summer and fall of the year 1952, a series of tape recordings of the Alpine transmissions were made at Bayport, Long Island, over a distance of approximately 50 miles. The results indicate that the reception of the second channel was uniformly superior to that of the 50 kw standard band New York AM stations. Some comparisons between the same program material transmitted on the second channel and a standard AM channel were obtained by receiving at the Alpine transmitter the FM signal of a New York AM station, transmitting it on the second channel and comparing it directly to the reception of an AM receiver of the same station's AM outlet. During heavy static, the comparison was of the same order of that demonstrated with simplex transmission in 1935 on the Empire State signal between New York and Haddonfield, New Jersey, a demonstration which many of those present here tonight will remember.

Like superiority was obtained during nighttime transmission when standard broadcast signals were garbled by selective fading and interference from stations located without the United States. The margin of superiority is sufficient to warrant the belief that a third channel can be multiplexed with performance better than that of the standard AM system.

DIFFICULTIES AND PRECAUTIONS:

With the solution of the transmitter and receiver problems, the sole remaining difficulty is that of the vagaries of the transmission path. The second channel in some localities will be affected by multipath transmission. Within cities, the effect will follow the same general laws of television multipath and can be treated in the same manner. The full extent of it will have to be determined by large scale experience.

CONCLUSIONS:

We believe we have demonstrated a system which provides a new dimension in the broadcast art. It is capable of being used in so many different ways for providing new services that we will not not attempt to enumerate or comment on them, other than to say that the practical broadcaster will in due course discover additional uses that we have never thought of. We would like, however, to point out that a system which can be made to operate on a field strength of less than 10 microvolts but which is restricted in its practical application by a Federal Communications Commission limitation of service area of F.M. stations to the 1 millivolt line is far ahead technically of the allocation plan imposed when a Commission, as formerly constituted, acted on the basis of incorrect technical information. Future demonstrations of the system will shed additional light on this aspect of the situation. Reports on these demonstrations will be made as they are conducted.

ACKNOWLEDGEMENTS:

We wish to make due acknowledgement of the work of Messrs. Richard G. Gillen, Armando Perretto, and the late Glenn Musselman, for the development and construction of the equipment, and to Perry Osborn and the staff of KE2XCC for its successful introduction into the practical art of F.M. broadcasting.

APPENDIX

The following demonstrations were made during the course of the presentation of the paper at Pupin Hall, Columbia University (distance to Station KE2XCC, Alpine, New Jersey, approximately 11 miles):

1. Transmission of the regular program from KE2XCC on both channels simultaneously with the speaker system switched alternately between them.
2. Transmission of the regular program on the main channel with the speaker system on the second channel and with the modulation on this channel removed at Alpine to demonstrate the freedom from cross-modulation by the first into the second channel.
3. Transmission of the regular program on the main channel together with a program from Station WASH-FM (in Washington, D.C.) on the second channel transmitted to Alpine via a high-quality wire line (approximately 250 miles.)
4. Transmission from KE2XCC of a binaural tape recording for simultaneous reproduction on the two channels at Columbia University.
5. Transmission of a tape recording on the main channel at KE2XCC simultaneously with a program received at Alpine from Station WALK-FM, Patchogue, Long Island, (50 miles) re-transmitted on the second channel.

In addition to the above mentioned multiplex transmissions from KE2XCC, the following series of tape recordings of the Alpine signals previously received at Bayport, Long Island (47 miles) were demonstrated.

1. A program from WALK-FM, Patchogue, was received at Alpine on an R.E.L. type 646 receiver, re-transmitted via the second channel of KE2XCC, and received and recorded at Bayport, Long Island. The recorded second channel signal at Bayport was compared with a recording of WALK-FM received directly (3 miles) on an R.E.L. type 646 receiver, similarly located. No difference in quality or noise level could be observed.
2. A second recording compared reception at Bayport on the second channel modulated by reception at Alpine of the F.M. program of a New York network station with the 50 kw AM transmission of the same station. The recording was made during early evening hours and for the reasons stated in the paper, the AM channel was unusable and the FM signal quiet.
3. A third recording was made under identical conditions with the preceding recording at the same receiving location, but was made during the afternoon hours under typical summer thunderstorm conditions (August 6, 1952). For the reasons stated in the paper, the AM channel was unusable, and the second FM channel quiet.

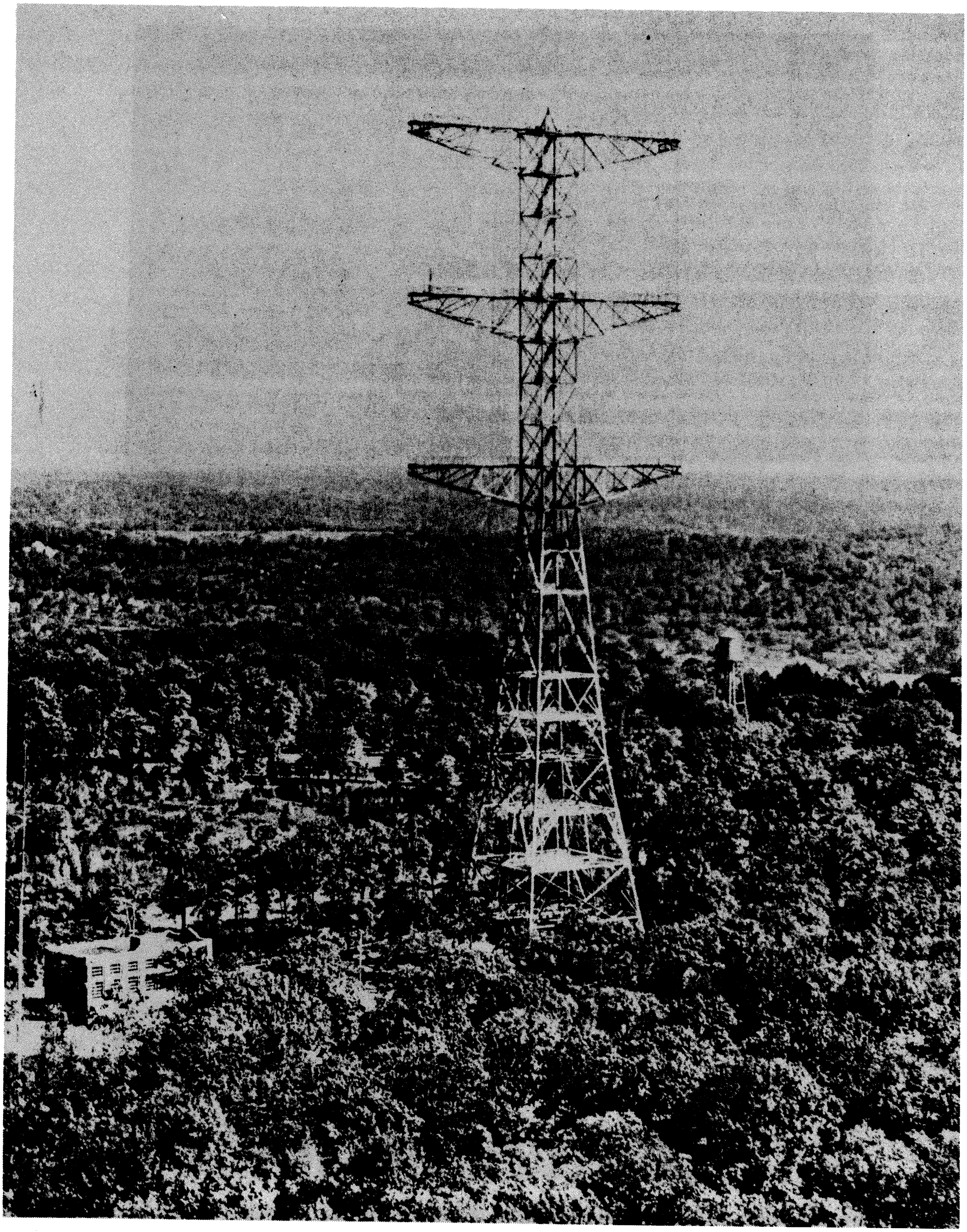

Fig. 9. Station KE2XCC located at Alpine, N.J. on the 500 ft. cliffs of the Palisades, approximately 17 miles north of New York City.

This picture was taken shortly after the station went into operation in 1938 on 40 megacycles under the designation W2XMN.

The Empire State Building in 1934. The two vertical dipoles at the top were originally for the sound and picture signals of the 120-line television tests. One of these was used for the Armstrong FM field tests.

FIELD TESTS OF THE ARMSTRONG WIDE-BAND FREQUENCY MODULATION SYSTEM FROM THE EMPIRE STATE BUILDING

by **Thomas J. Buzalski**
Chief Transmitter Engineer
NBC, New York

Presented at the Antique Wireless Association Annual Conference, Canadaigua, New York, September 1971
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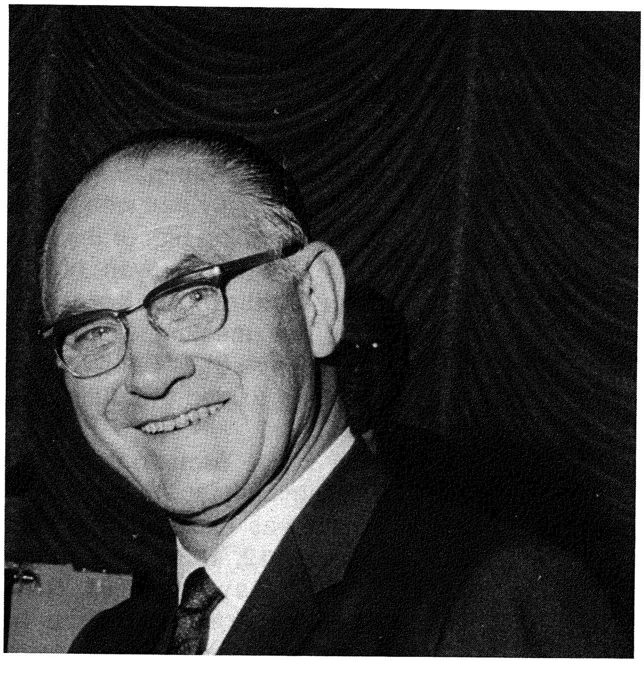
Editor's Note: The following paper is written from the unique vantage point of an engineer who worked closely with Major E. H. Armstrong on the early development of frequency modulation (FM), as an aural broadcasting service. Some qualities of Howard Armstrong as an engineer, inventor and human being are disclosed, not often found in print. His system of frequency modulation was in some respects a contradiction of accepted theory in that it achieved a reduction in noise level by using a channel having greater rather than smaller bandwidth. Armstrong was inclined frequently to say that one of the difficulties in what he was doing was that people so often knew so many things that weren't so. The development of Armstrong's system of FM stimulated work on information theory which provided a better understanding of fundamental communications principles which, in turn, has guided the design of today's complex systems.

Robert M. Morris (F 1990)
Editor, *A.W.A. Review*

Much has been written about Edwin Howard Armstrong and his four major contributions to the Radio Art. It is remarkable that nearly sixty years after his first disclosure, all four inventions are still in use. Frequency modulation as applied to aural broadcasting is, in fact, still developing in its service to the public. The last decade has seen an accelerating use of this method of broadcasting, with the advent of stereo and the increasing use of FM in cars providing some of the impetus. One might wonder how the Major would react to some of the sounds now heard on high-fidelity FM. The aural channel of the TV service has used FM throughout its commercial life.

Little has been recorded, however, of the first full scale FM field tests conducted by Major Armstrong at the NBC transmitting plant at the Empire State Building. It was my privilege to work with this man and to benefit from the expertise which he brought to bear on problems as they arose.

The National Broadcasting Company first occupied space on the 85th floor of the newly-completed but sparsely-occupied Empire State Building in September, 1931. An experimental television station was constructed to conduct tests on VHF using 120-line scanning with photocells for transmission. Cathode-ray tubes called kinescopes were used for picture reproduction, replacing the earlier techniques in which a neon plate lamp was viewed through a scanning disc.



Thomas J. Buzalski

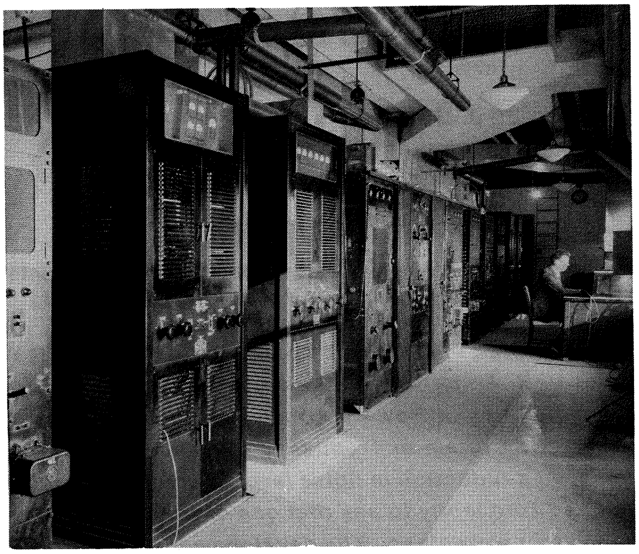
The early kinescopes employed a willemite phosphor which provided a picture in various shades of green. Perhaps some will recall seeing the green light in an otherwise darkened house during much of the early black-and-white TV era. The Empire State plant provided facilities for originating live and film picture signals with accompanying sound.

The picture transmitter was licensed as W2XF to operate on 44 MHz, and the aural transmitter as W2XK on 61 MHz. Separate antennas were provided in the form of vertical dipoles extending above the five-inch coaxial lines, and the transition from transmission line to antenna occurred at approximately ten feet above the top of the Empire State Building.

Extensive tests of this system of television transmission were conducted during 1932 and 1933. Although these tests proved the feasibility of using VHF for broadcasting, they also established that further substantial improvement in the quality of television picture transmission would be required before serious thought could be given to the development of a television broadcasting service. In the vernacular of the time, "Television was still just around the corner."

During this same period, Major Armstrong had been working on the development of wide-band frequency modulation at Columbia University. By the end of 1933 he had satisfactorily concluded initial tests of his method of wide-band FM telephony and had been issued four patents. At about this same time, he apparently met with David Sarnoff for the purpose of informing him of the new development, and may also have given him a demonstration at the Columbia laboratory. Probably as a result of this meeting, the NBC transmitting facility at the Empire State Building was made available to Armstrong to permit a full scale test of the new FM system.

The first visit of Major Armstrong to the Empire State Building transmitting facility is noted in a record of visitors which was maintained at that time. Under date of January 12, 1934, we find the following entry: "Mr. Beverage of RCA Communications and Major Armstrong here to discuss some experimental work which Major Armstrong expects to do here in the near future. " That visit was promptly followed by another on January 19, 1934. The notation indicates that Major Armstrong was there "to get information on W2XF for experimental work he is to do in near future". W2XF was the visual transmitter used in the 120 line television tests.



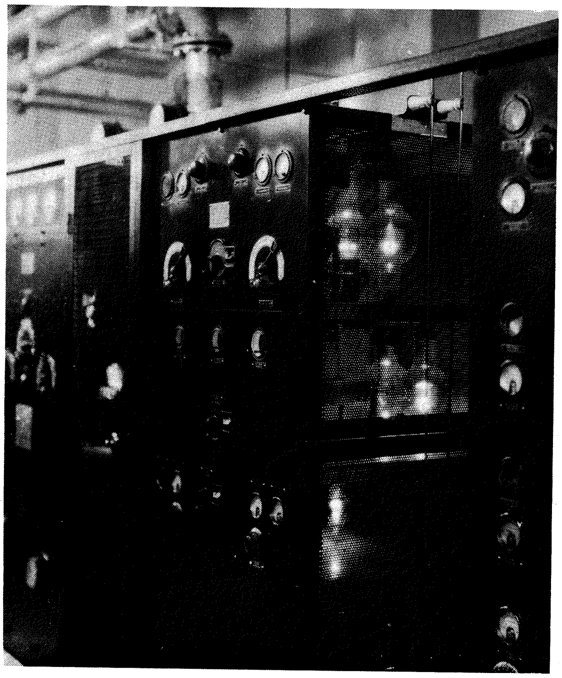
NBC VHF transmitters at the Empire State Building, circa 1934.

The power amplifier for W2XF consisted of two 846 water-cooled, neutralized tubes operated in push-pull at approximately 5 kW input power. Measurement of radio-frequency power in this portion of the spectrum -- with believable results -- was still in the future. Based on the difference between the loaded and unloaded resonant current drawn by the P.A., we believed the carrier output power was approximately 2 kW. The I.P.A. and the tripler used the 831 air-cooled triode (WL-674 and FP-2 were the Westinghouse and G.E. designations of the comparable tubes). The 860 screen-grid tube operating as a push-pull amplifier drove the high-power tripler. The overall frequency multiplication in the transmitter power was 24 times, provided by three doublers and one tripler.

During February 1934, the TV test transmission schedules were changed at Armstrong's request. Network programming was applied as amplitude modulation on W2XF in place of tone or picture signal. This portion of the test was probably directed to field observations on the coverage which might be expected of this transmitter. On March 26, measurements of the band-width of the radio-frequency multipliers and amplifiers as well as the band-width of the antenna system were initiated by Armstrong. Observations at both the transmitting plant and at the Columbia laboratory were correlated. It is now evident that the purpose of those measurements and observations was to assure that the FM signal could pass through the transmission system without distortion. The Major had long since learned to take nothing for granted.

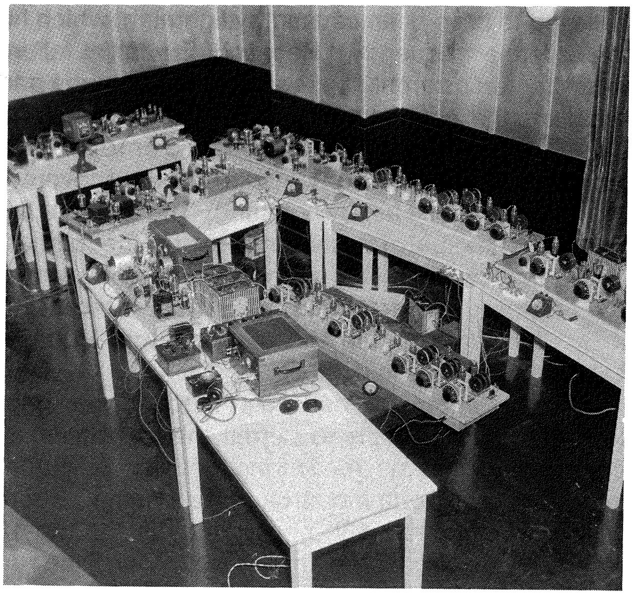
This meticulous approach uncovered several problems which were dealt with in due course. The antenna system offered a serious mismatch to the coaxial line, thus restricting the effective bandwidth of the antenna system. The radio-frequency stages in the transmitter were designed for maximum efficiency since, in the design application, no bandwidth requirements were imposed on the driver stages. Both of these problems were effectively resolved with assistance from P.S. Carter on the matching problem and John Evans on the circuit problems.

During May 1934, Major Armstrong had FM exciter equipment suitable for driving the low-power stages of the transmitter moved into the television studio space on the 85th floor, adjacent to the transmitter. Tests and adjustment of the equipment was started at once. Also, in May of 1934, NBC received an experimental license which had been requested to cover experimental operation of the television picture transmitter on frequency modulation. W2XDG was assigned to operate on 40.6 and/or 41.0 MHz for this purpose. A field-intensity survey by RCA Victor engineers was promptly conducted at Armstrong's request.



Transmitter at W2XDG used in the field tests. This view shows the 831's in the tripler and intermediate power amplifier.

The FM test from W2XDG started on June 2, 1934 on 41 MHz; the total time of operation during June was 49 hours. The antenna transmission line matching project was completed on June 6 and, on the evening of June 20, 1934, a special demonstration of organ music was transmitted for observation by General James G. Harbord, the then-Chairman of the Board of R.C.A.



Armstrong frequency modulation exciter equipment, used in the 1934 - 1935 field tests, at the Empire State Building.

The FM exciter equipment as set up in the shielded TV studio was composed of a number of classical "breadboard" units. This type of construction provided adequate performance and excellent access, but it obviously did not conserve space.

It should be noted here that while standards of operation and adjustment were established and maintained by the Major, the responsibility for operation in accordance with the terms of the license was in the hands of the NBC technical staff. This meant that close relations and cooperation had to, and did in fact, exist between the Major and the NBC engineers. Telephone communication was frequently employed between the point of observation, -- for example Harry Sadenwater's home at Haddonfield, NJ, -- and the transmitter plant, to permit optimum interchange of information. Thus the mode of transmission or the nature of the modulating signal could be in full accord with the

Major's requirements. Similarly, when discrepancies appeared, the cause could be quickly isolated and corrections applied.

Tests were conducted through July with facsimile signals being added for test transmission to Haddonfield. However, trouble developed on July 30, 1934. The large insulator which supported the upper section of the center conductor of the coaxial line as well as the antenna rod for W2XDG/W2XF, had failed. Initially the failure was believed to have been caused by lightning, which hit the antenna frequently. Repair of the initial failure was effected promptly by removing the antenna and replacing the insulator with an identical spare.

When the antenna was removed, a substantial number of pit marks were discovered. These were tracks left by lightning. The fact that the two experimental TV antennas were the highest points in New York City and were frequently struck by lightning made them of much interest to K.B. McEachron of the G.E. High Voltage Laboratory at Pittsfield, MA.

Arrangements had been made a year prior to the Armstrong tests to permit the installation of current and voltage measuring devices to gather information on lightning stroke phenomena. There were approximately 180 pock marks in the top 18 inches of the two inch diameter rod. Since the rod had been in service for three years, this suggested the occurrence of approximately 60 strokes per year. McEachron acquired the original rod and, judging from marks made in the same material in the lightning laboratory, stated that some of the strokes achieved a peak current on the order of 100,000 amperes.

A second antenna-insulator failure of the same type during September led to the conclusion that the failure was caused by excessive heating due to the poor dielectric characteristics of the porcelain material at VHF. Action was then initiated to have a special insulator manufactured and Steatite, a material having a much superior high-frequency characteristic, was specified. Since delivery of such a custom-made insulator was estimated to be 6 months, RCA Communications prepared a temporary replacement made of rings of Mycalex. A coaxial-line test set-up was prepared for testing these insulators at 41 MHz and, as a result of this test, the superiority of Mycalex over porcelain in this application was clearly demonstrated.

W2XDG was returned to service on October 10 with substantially increased radiated power, attributable to the reduction of loss in the temporary Mycalex replacement insulator. During October, Armstrong commenced multiplex program tests in which two separate programs were simultaneously transmitted and successfully received at Haddonfield. These tests continued into November 1934 with four simultaneously transmitted channels comprising program, facsimile, synchronizing for facsimile, and telegraph.

When Major Armstrong planned to make adjustments to or measurements on the performance of the FM signal generating system, he would usually phone in the morning to advise that he would arrive after lunch, meaning some time between 2 and 3 PM. After a few words of greeting and an outline of projected demonstrations, the Major would shed his jacket and frequently his shirt and tie as well, and proceed with his work in the studio. He was sometimes unduly secretive about his objective or the nature of the problem he was trying to solve.

Time meant nothing to him. The 5 PM quitting hour would come and go but Howard would continue to tinker. However, when an acceptable stopping place was reached, he would confess to the need for some nourishment and more often than not would take all hands out to dinner before turning us loose. Those were memorable occasions during which incidents in the early history of radio would be colorfully related.

We sometimes wondered about the Armstrong lunch. When Howard appeared at Empire State after lunch, he was obviously full of vim, vigor, and vitality. Harry Houck recently related a story which sheds some light in this area. It seems that Tom Styles frequently accompanied the Major at lunch when the center of activity for the day was at the Columbia laboratory. One day the lunch counter which they usually frequented was closed. Tom, always eager for a good meal, induced the Major to try a nearby French restaurant. After carefully studying the exotic fare offered, Tom ordered frog legs provinciale. When the waitress addressed the Major, he ordered a cheese sandwich and a glass of milk. Tom remonstrated, saying, "Look, Howard, you always order a cheese sandwich and a glass of milk. Let's make this a little special occasion." The Major regarded Tom quizzically, passed his hand over his bald pate, and said, "Tom, you're right. We should make it a special occasion. Waitress, make that two cheese sandwiches and two glasses of milk."

During important demonstrations of the system Armstrong would arrange to have Jack Shaunessey be with us, just in case of some unforeseen problem with the FM equipment. On one occasion consternation arose when, in making a periodic routine test of the system, no signal emanated from the FM generating equipment. It was Jack who asked the 64-dollar question, "Did anyone charge the storage batteries?" A new set of batteries complete with spares and a charger assured the end of that problem.

It might be appropriate at this point to describe the receiving setup in Haddonfield, NJ where Armstrong gave many demonstrations during these tests. Harry Sadenwater of the RCA staff, who was also a member of the Radio Club of America and a long time friend of Howard Armstrong, lived in a nicely situated home with an ample back yard in Haddonfield. This site, approximately 80 miles from the Empire State Building, was an almost ideal spot, from the Major's point of view, to demonstrate the superiority of FM over AM broadcast reception from New York.

The receiver comprised several radio cabinets containing the intermediate-frequency amplifiers, the limiters, the discriminator, and the audio amplifiers. These were preceded by a high-frequency converter consisting of a modified RCA Communications high-frequency receiver. The units were set up in the Sadenwater rumpus room in the basement, hampering the intended use of the bar for many months. The antenna was carefully chosen since it consisted of a vertically-polarized half-rhombic. The center was supported by a 60 foot vertical mast and the antenna was, of course, oriented toward New York. The rhombic was later supplemented by a vertical dipole mounted on the side of the house.

In order to insure our involvement and cooperation, the Major entertained those responsible for the operation of the Empire State facility and ran a special demonstration for us at Harry Sadenwater's home in Haddonfield.

In December 1934, steps were taken by NBC to re-equalize the two program circuits from Radio City to Empire State. These circuits had been equalized to 10 kHz, but new equalizers were prepared to bring the response flat within 1 db from 30 Hz to 14 kHz. This was undoubtedly part of Armstrong's plan to establish and demonstrate FM as a very-high-fidelity system. Radio City, with its new studios and equipment, had uniform frequency response to at least 15 kHz.

Early in 1935, activity centering on the Empire State transmitting facility grew to a crescendo. In addition to the Armstrong tests, RCA was studying propagation characteristics of the FM frequencies as well as other portions of the spectrum, and preliminary comparative tests of AM vs. narrow-band FM vs. wide-band FM were conducted concurrently with tests and demonstrated by the Major.

On May 7, 1935, at the annual stockholders meeting of RCA, David Sarnoff announced development of a much improved system of electronic television, and plans to start field tests in less than 15 months. This meant that conversion of the Empire State transmitting equipment would have to start very soon. It also meant that the use of the transmitter by Major Armstrong for FM tests would have to be terminated. Plans for completely rebuilding the antenna and transmitter plant were being developed under forced draft and personnel unfamiliar with the plant were being trained to operate the existing facility and make the planned modifications.

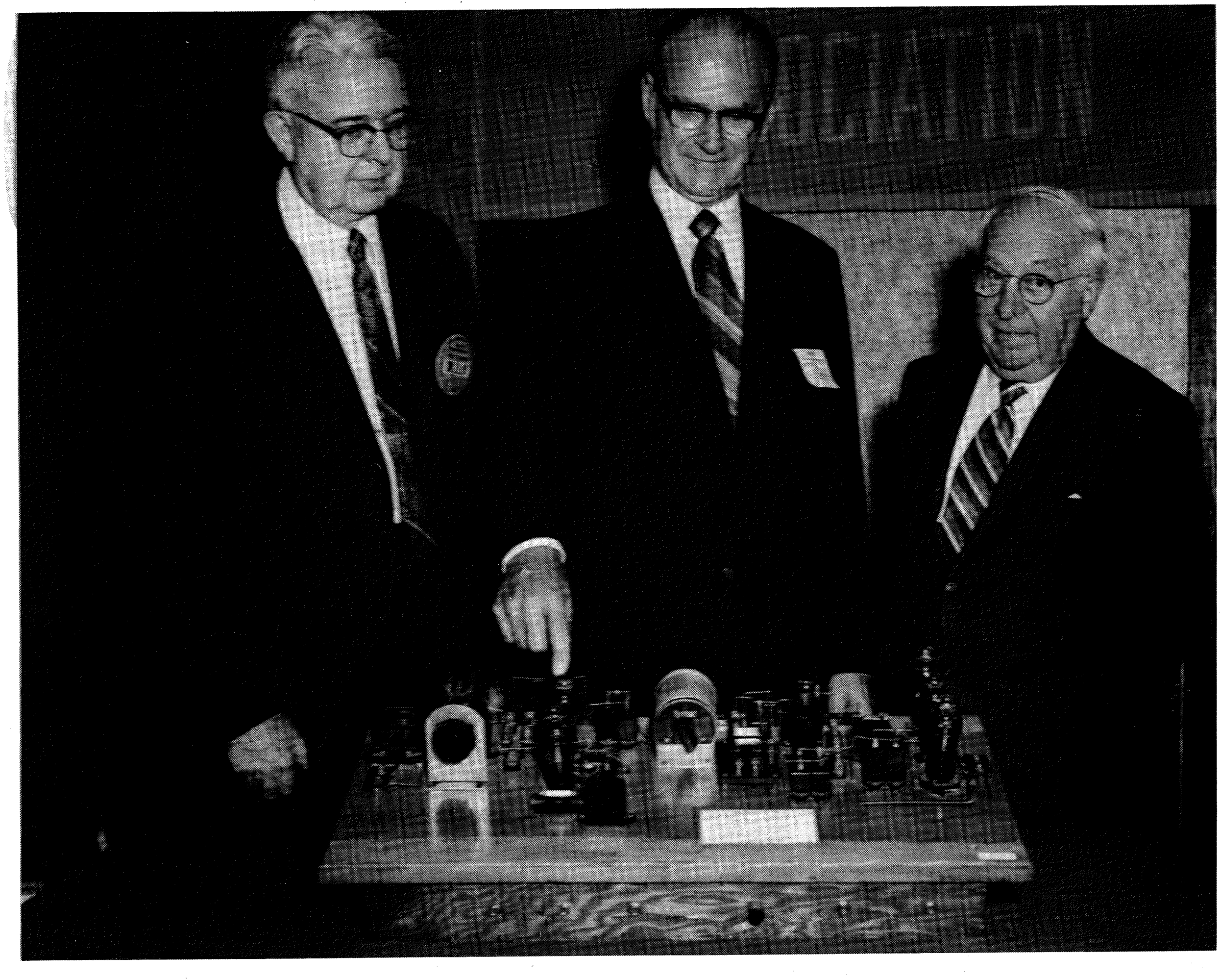
During June, July, and August of 1935 final improvements of the FM equipment were made and tested. Further demonstrations were given, with reception usually at Haddonfield. The Major was quite fond of comparing FM reception on VHF with that of the 50 kW WEAF transmitter on Long Island on a warm August afternoon when there was a nearby thunder storm. Reception of WEAF was, of course, badly marred by the heavy static whereas the FM reception from W2XDG was crystal clear.

In October 1935, the aural transmitter rebuilding had been in progress for more than two months and parts for the modification of the visual transmitter were on hand. With Armstrong's reluctant permission, the FM equipment in the studio was dismantled so that the studio area could be used for some of the required construction work. Thus the FM field tests by Armstrong at the Empire State Building were terminated.

It should be apparent from the foregoing that much was learned during the course of the FM tests that is now taken for granted as an established part of the radio art. The importance of antenna impedance matching to the transmission line and of using low-loss insulators at high frequency, the necessity of designing antennas so that points of mechanical support are not at high-voltage points, to say nothing of transmitter considerations, were well learned during the FM field testing. It is interesting to note that two years later, when the Major decided to build his own FM station at Alpine, he ordered a high-powered transmitter from RCA.

After the death of Armstrong early in 1954, it became necessary to dispose of the large collection of equipment and material which he had accumulated over the years. This included electronic gear involved in all of his inventions and developments, from his regenerative receiver and the first superheterodyne to and including the FM equipment used in his many tests and experiments. This equipment was stored at his old home in Yonkers and at Columbia University. It fell to Armstrong's long time friend and associate, Harry Houck, to rescue this material from the junk man and oblivion. It was trucked to a large red barn in Northern New Jersey, where it was stored for many years. A few pieces of breadboard equipment have been identified as those used in the Empire State tests. It was Harry Houck's intention to identify, preserve and suitably display those pieces of equipment which constitute a significant part of the Armstrong story.

I hope it is evident, but perhaps it should be stated, that I considered it an exceptional privilege to have had the opportunity to be closely associated with Major Howard Armstrong during the development of FM, and to have had the opportunity of observing perhaps the world's greatest development engineer at work.



Messrs. Robert M. Morris, Thomas J. Buzalski, and Harry W. Houck
With the original FM exciter used in the Empire State tests.
Photographs courtesy of Robert M. Morris and The Antique Wireless Association.

THE ARMSTRONG FM LITIGATION

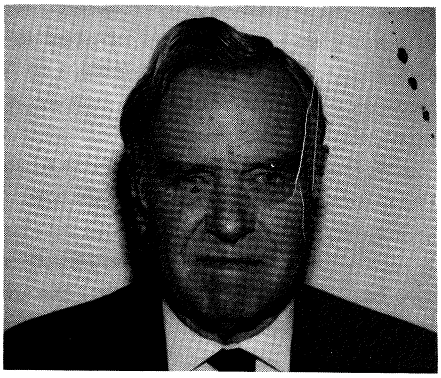
by **Dana M. Raymond, Esq. (M)**

Presented on the Occasion of the Tenth Anniversary of the New England Wireless and Steam Museum, Inc.
East Greenwich, Rhode Island, September 7, 1974

INTRODUCTION by Robert W. Merriam:

In 1964, Harry W. Houck presented a talk at the New England Wireless Museum that will be long remembered. He described his experience with Major E. H. Armstrong in developing the superheterodyne from the days in France to the time of the first finished model which he built in New York. As supporting material for his talk, he brought this splendid model and explained it to us in detail.

Harry Houck is a remarkable man as well you would expect the co-inventor of the superheterodyne to be. To give you a picture of the man, here is a brief passage from *Man of High Fidelity*:



Dana M. Raymond

"Late in 1917, there appeared on his staff a belated recruit in the person of Sergeant Harry W. Houck, a Pennsylvania Dutch boy from New Cumberland, Pennsylvania, a tiny town just south of Harrisburg. He, too, was destined to be added to the long list of friends and associates whom Armstrong drew around him over the years.

'Houck had been an eager young wireless "bug" in the fastness of New Cumberland and had been assigned to report to Captain E. H. Armstrong at 140 Boulevard Montparnasse, Paris. He arrived there late under fantastic circumstances. As he stood before Armstrong and snappily saluted, he was wearing a uniform half French and half American, and officially had been pronounced dead.

'On landing in France, he had been taken violently ill and had been rushed into a base hospital where the ministrations were none too solicitous.In a delirium one night, Houck wandered away across the fields and woke up in a French hospital more to his liking, with two French doctors bending attentively over him. When he was released two weeks later, he gave his base hospital a wide berth and hopped a truck for Paris to report for duty, per orders.

'There he discovered that the base hospital in one of those mix-ups peculiar to armies, had reported him dead and had so notified his family and Captain Armstrong.

'Armstrong was charmed by all this and by the perseverance that had carried Houck to Paris and began questioning the new recruit to find out how much he knew about wireless. Asked to draw a crystal circuit, Houck quickly complied. Then, anxious to show off his knowledge, he volunteered that there was a new and better one than that, and he swiftly sketched a feedback circuit. Armstrong gravely watched, quietly switched two lines about which Houck had reversed in his excitement, and asked where he had heard about it.

' "In *Wireless World*," said Houck, "and d'you know, Captain, the feller who invented this has the same names as you!"

'The new sergeant turned out to be a craftsman in the building of apparatus meticulous enough to suit even Armstrong who was a stickler for cleanness and compactness of design. Moreover, he had the patience, enthusiasm and stamina to match Armstrong's disregard for time when in pursuit of a problem.

'In after years Armstrong would allow no one else to build his transformers, maintaining that Houck had a "touch" with transformers superior to anyone he knew. In addition to this, Houck had a sound streak of originality, capable of following new ideas and carrying them out on his own. Early in 1918 in France, the two were soon in pursuit of the problem."

Here, in 1974, at the annual meet of the New England Wireless Museum, we are again addressed on an Armstrong subject by the distinguished lawyer, Dana Merriam Raymond, who has served the major and his estate so ably. The primary purpose of this paper is to put Mr. Raymond's valuable remarks in the record. Another passage from *Man of High Fidelity* tells of the beginning days of FM and, perhaps, adds a small perspective to Mr. Raymond's talk:

> "By 1941, there were over 500 FM station applications on file with the FCC and over twenty-five licensed FM manufacturers. As a kind of flourish to this victory, Armstrong in January 1941 donned ice-cleats, a parka and a huge woolen cap, and climbed to the top of frosty Mt. Washington in New Hampshire to inspect the Yankee Network's FM relay station in operation under the worst icing conditions.
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> 'In high spirits, the Major telephoned Harry Houck early the next morning from the mountain top. "Harry," he said, "I'm looking at the most beautiful sunrise I've ever seen." Houck who was looking bleary-eyed at the New Jersey darkness, was unable to appreciate the spectacle.
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> 'Armstrong had grown increasingly fond of New England, and Marion Armstrong had no trouble sometime before in persuading him to buy a big rambling house at Rye Beach, New Hampshire, where they spent holidays and summers, and from which he now watched the FM revolution spread over New England. It was the Yankee spirit and Yankee enterprise, he felt, which had given FM its first chance to show its worth -- not the patent lawyers of the New York board rooms, nor the merchandising seers of Radio City, nor the pin-striped geniuses of Madison Avenue -- and he developed a deep affection for the region.
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> 'Only brief interludes could be spent at Rye Beach, however, for the FM development was crowding all his time. He added two more graduate engineers to his laboratory: Bill Hutchins and Bob Hull. McCormack, his lawyer, already had taken on a young Columbia Law School graduate, Dana Raymond, to aid in handling the mounting FM business. FM stations were rising on all sides. In quick order, WQXR in New York, WHAM in Rochester, WTMJ in Milwaukee, WMCR in Washington, and WBNS in Columbus added FM to their broadcasting services."

The likelihood of one single person making all four of the most important radio receiver inventions is truly an unbelievable statistical happening. Major E. H. Armstrong did it. What force started him ?

Some old correspondence which has been recently made available to the museum through the kindness of Mr. Charles Reginald Underhill, Jr. has firmly established a chain of influence which began with Walter Wentworth Massie in Rhode Island and passed through Mr. Charles R. Underhill, "the magnet man", to Edwin Howard Armstrong and thence to the world.

Before 1907, Mr. C. R. Underhill, the authority on magnetism, was employed as an electrical engineer for a magnet wire firm in Providence, R.I. Here, he met Massie and formed a friendship which lasted until Massie's death in 1941. Underhill worked on his printing telegraph in Massie's station at Block Island and the two engaged in enthusiastic wireless discussions while they both lived in Rhode Island. These two men even jointly authored a book on wireless telegraphy which had the blessing of a lengthy supporting passage by Nikola Tesla.*

In 1907, Mr. Charles R. Underwood moved with his family to Pinecrest, New York, nearby the Armstrong household. But here it is in Mr. Underhill's words from a letter to his son dated August 27, 1946:

> "For nearly two years from 1907 to 1909, Howard visited me after school at our home on the old Pine Crest Estate, North Broadway, Yonkers, New York, coming at first on a bicycle and later on a motorcycle. I was working on my book *Solenoids* at the time and making drawings on a large drafting board in my den. Howard would sit nearby, leaning back in his chair with his head against the wall, and ask me a question to which I replied while drawing.
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> 'Howard would meditate for awhile and then follow up with another question. This often went on for hours at a time. During one of his visits, I gave him the first vacuum tube he ever saw. It had been given to me by deForest's chief engineer, Mr. Babcock, for experimenting with my wireless printing telegraph."

An inscribed portrait of Armstrong carries the same message as does the following passage from a letter written by Major Armstrong to Mr. and Mrs. Underhill in 1948:

> "Who of us in the old days at Pinecrest could have realized the value of the instruction that I was receiving in the fundamentals of 'wireless' and what made it go ? But perhaps the greatest lesson that I learned there was the lesson of the skeptical approach to the things in the books that failed to agree with one's own experimental observations.
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> 'How well do I remember the day when I expressed concern because a spark transmitter that I was using gave best results with connections different from those recommended in one of my three 'wireless' books. I felt and said that there must be something wrong with my equipment or my technique. And I remember the answer I

Massie, Walter W. & Underhill, Charles R.*, **Wireless Telegraph and Telephony, *1909, D. Van Nostrand Co., New York* received from you so well that I can repeat the words that were used -- "What do you care about what's in the book ? You're an original thinker" -- followed by an exhortation to believe in my own experimental ability. I remember it so well because it was the first time that anyone ever suggested that I had any particular ability in what was implied by the then miraculous words "original thinking." 'Today, while it has become an established historical fact...that I made the Regenerative Circuit invention, I think that yours is unquestionably the credit of having inspired it. The lesson that the things that are not in the books are the most important of all was the most valuable lesson ever given to me."

Armstrong freely acknowledges his debt to Mr. Underhill. Mr. Underhill certainly was an able electrical engineer before he came to Providence but it is quite likely that he learned a good deal about wireless from Massie as Massie had been experimenting in the field since 1897. Armstrong was interested in Massie's work as late as May 1937 when he talks of Massie's coherers in a letter to Mr. C. R. Underhill at that time.

Thus was formed this curious chain of influence beginning in Rhode Island, extending to Yonkers by way of Mr. C. R.. Underhill, "the magnet man", and to the world through Major Armstrong's genius.

ADDRESS of Dana M. Raymond, Esq.:

I'm very happy to talk to you about Major Armstrong and I was pleased to see his picture in the meeting house and the radio building of the museum. I met Major Armstrong in 1939 shortly after I graduated from law school and I knew him very well. In fact, my work with him was the main part of my life for many years.

Major Armstrong's life in one sense was a tragedy. He was a millionaire before he was 30 years old. He had a beautiful wife. He received many honors in his profession and yet he, at about the age of 63, died -- he committed suicide in New York. He believed that he was a failure -- that he could not win. He was broke.

Major Armstrong is one of the greatest inventors that this country has produced. His picture is in this museum with Nicola Tesla, Edison, Alexander Graham Bell -- and he belongs in that line. I should go on to say that he's not the last, there have been others since. One that I can think of is Charles Townes who invented the laser and who, in recent years, has received the Nobel Prize. However, Major Armstrong was one of the greatest.

Now it has been said by some that there was some conflict between industry and Major Armstrong that caused trouble. I don't look at it that way and I knew him well. He was a man born to struggle, strive and, I suppose, to suffer. He was a tireless worker. He was a proud man -- a stubborn man -- and one of the ironies of the whole situation is that after his death, his widow carried on and he was completely vindicated.

The decisions in the courts were in exact accord with what Major Armstrong had said about his own work and, as a result, it turned out that he left a very substantial estate.

Now if he had been a more flexible man, not so much of a lone contender, perhaps he would have carried on and been alive when it happened. And yet on the other hand, if he had not been the kind of man he was, he might not have bucked through the stone walls of radio theory and practice as he did in the 1930's with his development of FM. I'm not going to speak about his earlier developments, the regenerative circuit, the superheterodyne and the super regenerative circuits, any one of which would have made him very famous.

His work in FM began in the late 20's and 30's when he was about forty years of age. His patent on what is called wide-band FM was issued on December 26, 1933 to run for 17 years. Now in this patent, Major Armstrong explained the transmitter and receiver that he had, and explained his principle for reducing noise in radio signaling, and stated that he had observed a reduction in noise of 100 to 1. Now that meant that he claimed to have a static eliminator, and I'm sure that many people here know what static eliminators were in the early days.

A static eliminator was like a perpetual motion machine. It was impossible of achievement. It was accepted theory in radio at that time that when noise or static came into a receiver, it was manifested in radio waves in the same way as the signal that you were receiving. When it was there, if you amplified the signal you would also amplify the noise and static and it would be in the same ratio to the signal coming out as coming in.

It was "known" that the only thing you could do about it was to have more power in the signal so as to override the noise, or you could use directive antennas so as to block out noise coming from directions other than the direction of the signal, or you could narrow the band of communication as this noise was known to be spread over the whole electro-magnetic spectrum and the wider your receiver, the more noise you would capture in the receiver. Major Armstrong not only had what was a static eliminator but the course he took to reduce the noise was in direct conflict with established theory and practice.

I'm supposed to be talking about litigation here tonight. This was in 1933; I think I can tie it into litigation this way. Twenty-five years later, there was a suit in the Southern District of New York against the Emerson Company and we had one of our witnesses, Dr. Raymond Heising, of the Bell Labs -- a number of you here probably knew him long before I did -- at any rate, he was the inventor of the Heising modulator and a distinguished engineer. Dr. Heising explained to the court what I have explained here and also told about the Bell scientists who had worked on the subject and written papers; but the way he brought it home was by the facts of what happened. He told about how, at the Bell Labs in early 1934, they got a copy of Major Armstrong's patent. Major Armstrong was very well known and they would look at any patent issued in his name. They read this patent and passed it around and they said: "Well, Armstrong must be crazy this time."

It was filed away. Three years later, they read on the front page of *The New York Times* that Armstrong was receiving signals at West Hampton, New York from a little station on top of the Empire State Building, of one kilowatt. So they decided at the Bell Labs that they'd look into this matter again.

And as Dr. Heising told the judge: "We thought it couldn't be done, but Armstrong had done it." Now, that is about the best kind of testimony that you can have in a law suit on the question of whether a man has accomplished something of significance.

There was another person that he had as a witness, Paul de Mars. He told the court about being retained by the Yankee Network in the early thirties to investigate the matter of setting up a system of short-wave broadcast stations in the New England area. These were to be placed on mountain tops to extend the coverage, and he investigated the matter for a number of years. In 1935, he had come to the conclusion that it would work but it wouldn't be any better than the standard broadcast system and since it wouldn't be any better, it was not an economically feasible alternative for broadcasting.

Just after reporting his conclusion to the Yankee Network, he happened to hear of proceedings before the Federal Communication Commission where Major Armstrong was making a pitch, you might say, to get some frequencies set aside for some experimental broadcasting with his new system. Paul de Mars went down to Washington and he heard the recordings which Major Armstrong had prepared for the Federal Communications Commission

When he heard those recordings, he was stunned, as he said, and he completely changed his mind concerning the feasibility of short-wave broadcasting.

The Yankee Network thereupon embarked on putting up FM broadcast stations, one on Mt. Asnebumskit and one on Mt. Washington at a time when there was not a single receiver anywhere in the United States that could pick up the new FM signal, and when the Federal Communications Commission hadn't even authorized such a broadcasting system. He and John Shepard were convinced that FM was bound to come, and the Yankee Network went ahead.

Now Paul de Mars told the court about this and, as a result of his personal knowledge and that of John Bose who worked with Major Armstrong, we were able to play those recordings in court as Major Armstrong had put them on before the Federal Communications Commission 24 years before. I can remember one of them was *June in January* and the recordings -- the difference between the FM one-kilowatt station and the AM 50 kilowatt clear-channel station, transmitting similar programs, was so striking that it was almost pathetic.

Now in the second case that we had in Chicago -- this matter had to be tried twice -- the court had appointed an impartial expert, Dean George R. Town of Iowa State University. The Dean sat through all of the trial and he heard the recordings. When it came his time to testify -- counsel for both sides were entitled to ask him questions -- I asked Dean Town if he had heard the recordings and then I asked him: "What do you think of them ?"

That's all I asked him about the recordings. And I'll never forget Dean Town's comment. He said: "I was very interested in hearing them. I knew that such recordings were in existence but I never heard them and I could not help thinking, as I was listening, that what they showed was well known to every engineer in this room," -- there were many on both sides of the case -- "but I also couldn't help thinking how remarkable it must have been in 1935 when people were not as familiar with frequency modulation as they are today."

That also would have been enough, you would think, to end the case. And there was another man who testified: Frank Gunther of Radio Engineering Laboratories -- the company that had built some of the first FM equipment. Another man was Harold Beverage of the RCA Communications Company. I had asked Dr. Beverage to testify at the trial. He had known Major Armstrong well and had known his work from the very beginning, but he felt that he had to decline because of his association with RCA and the fact that Armstrong's first suit had been against RCA.

At the trial, it turned out that Dr. Beverage's name was mentioned quite a few times one way or another, and one day the judge said: "I'd like to hear from Dr. Beverage. He seems to have been a mountain in these matters."

He actually was a big man physically and in reputation and esteem among his colleagues. So it was arranged that he would be subpoenaed and he came in and testified. Without reference to patents or records, he knew just what it was that Armstrong had done and he explained to the court how the wide-band system was used in the mobile communications field -- where the band widths are narrow as compared with the broadcast service -- and how the same principle for noise reduction was employed in both.

Those things that happened in the early years were reflected in the litigation and played a great part, I think, in the successful outcome of the litigation. Now to go on with Major Armstrong.

Seven years after his patent was issued in 1933, affairs had developed to the point where FM could be established as a broadcast service. That was done in 1940 for FM broadcasting; in the next year, 1941, FM was authorized as the sound channel for the television service which was established at that time. A number of companies had become interested in the commercial sale of FM equipment. There was a great deal of public interest and, at that time, nearly every company that was really interested in pushing FM, recognized Armstrong and had taken a license under his patents.

Then, in 1941, there was Pearl Harbor and, in due course, commercial production of all types of radio equipment was stopped so that the radio companies could concentrate on production for military purposes. All this time, Major Armstrong's patent was running out.

Major Armstrong, at that time, made a gesture which very few men have made, I think. He granted a royalty-free license to the United States government under his FM patents. The first great use of FM was during World War II for military communications. There were hundreds of millions of dollars worth of FM equipment built for use in tanks, for the Navy, and in walkie-talkies.

Now Major Armstrong did that against the advice of his lawyers. Had he not done so, he would have received -- I can't say how much money -- but it would have been in the small millions of dollars. Major Armstrong knew that he was going to be working for the government as he did all during the war, and he did not want to be in a position where anyone might think or say that any advice that he would give on a radio matter might have been influenced by whether he would get any return from it.

What he did was something that a corporation could not have done because it could not have been justified in the eyes of the stockholders. What he did amounted to a gift. But he was a big man with a broad view, and he acted accordingly.

After the war, the commercial production started up again and, by 1948, it was well under way. The companies that had taken licenses from Armstrong continued their licenses, but there were other companies that had become interested in frequency modulation, in selling equipment, and since Armstrong's patent had only two or three years to run before it expired, it turned out that many of those companies did not take licenses. In 1948, Major Armstrong filed suit against RCA, the most important company in the industry.

Major Armstrong felt that if he could prevail in a suit against RCA or work out a settlement with RCA, that would resolve the matter with other companies. That litigation started in 1948, went on to 1949 then to 1950 when his patent expired, and continued on for three years until his death.

In 1950, his royalties had stopped with the expiration of his patent. His expenses continued. He had the Alpine station; he had a laboratory. He had very great legal expenses, and he died at the beginning of 1954 after having filed 20 suits against other companies. He had to file such suits because of -- lets call it -- the statute of limitations in these matters. Large production had begun in 1948.

By the beginning of 1954, six years had run and, under the law, there could be no recovery for anything which happened more than six years before the suit was filed.

When he died, his assets consisted primarily of 21 unresolved law suits. His widow, Mrs. Armstrong, is quite a woman. At that time, she received advice from many people that the lawsuits ought to be settled on any terms. Her husband had spent ten years in what was like a war and there should be an end to it. She came to feel, however, that she was going to carry on and we worked it out so that we settled cases and tried others. Our objective was to get the matter resolved and, at the same time, to resolve it right. We were prepared to go to trial and, of course, that was very important in getting any settlements.

In 1958, the case came on for trial in New York before Judge Edmund Palmeri. The way things work in this country, this case -- one of the greatest in the development of radio -- was to be tried on the merits by a lay judge. Judge Palmeri was a Phi Beta Kappa. I think his field was English literature. I don't think he had ever heard of a condenser. He didn't have the faintest idea of what was meant by band-width. But the case was assigned to him and the trial took five weeks. Mrs. Armstrong was there every day. You might find it hard to believe but actually a trial of this kind can be very dramatic; there is a lot of tedium and boredom in it, to be sure, but there are also many, many times when it's intense and deadly serious.

I won't try to go into all that was involved in that trial. I might just mention a comment that Judge Palmieri made long afterwards about the situation he was in. After the five weeks trial, he got briefs from the two parties about a foot thick. The record that he had was even thicker. Judge Palmieri said that sometimes he felt like a flea on a mosaic and that every once in a while he would try to jump up and see if he could get an idea of the pattern.

After hearing me, you wonder now why was it if there was this great invention that Armstrong made -- what was all the hollering about -- why did it take a five weeks trial -- why did it take two trials before it was finally resolved ? On that I just want to say that there were defenses -- there were many, many defenses but there were some defenses that -- as I was saying to Bob Morris at lunch -- honorable, reasonable, experienced men could believe had merit.

One of them, in fact the most important one, was that even if it was conceded that Major Armstrong had made a tremendous contribution in radio -- had opened up a new line of radio by his FM work -- still his discovery was too broad to be something that could be covered by a patent. Patents are intended to cover improvements in the commercial arts. Generally, they are about a machine or a process which is rather specific.

But here was a discovery which purported to blanket a whole industry. His patent covered all FM receivers in the broadcast field, all the transmitters, all the police communications although there had been great changes in circuit design since his patent had issued in 1933.

There certainly was little visual similarity between the two tables full of amplifying equipment that Major Armstrong had for his first receiver, and the little portable receiver which was charged with infringement about 25 years later. They said it was like a law of nature -- it was too broad and vague. Now that was a matter that lawyers and business men in the industry could have different opinions about.

There was another defense which was equally serious from one standpoint and that was that this kind of suit is supposed to be against somebody who has infringed the patent. In the case of Armstrong's invention, his invention was in the transmitter and the receiver. The whole transmitter must be designed to provide a wide deviation to the carrier -- several times the range of the audio band being transmitted -- and the receiver must be adapted to receive this wide-band wave and have limiting so as to be responsive to the wide-swing signal and discriminate against the noise.

The transmitter itself was not the invention; the receiver was not; both had to work in cooperation to get the results of noise reduction. Now the way our radio industry is organized, the receivers that are purchased by the public are manufactured by companies that make only the receivers; they don't make any transmitters. Of course, the members of the public don't operate a transmitter; they only receive the signal which comes over the air and tune their receivers.

I shall never forget Floyd Crews, the lawyer for Emerson. He started his final argument, one year after the trial, by saying: "The Emerson Company has never turned on a transmitter nor has it turned one off; it has never manufactured one. All it has done is to manufacture receivers and sell them to the public, and the public uses our receivers to pick up signals that have been authorized by the Federal Communications Commission, a government agency. There hasn't been any infringement on the patent." Now, curiously, there had never been a case that had involved that particular situation; the defendant had normally been someone who was practicing the entire invention or who was aiding someone else to practice the invention. That was the principal defense.

I hope you will forgive me if I say that I think that justice was done. I want to thank you for letting me talk a little about Major Armstrong.

MINIATURE BIOGRAPHIES

#1 - *THE ENCYCLOPEDIA AMERICANA*...Robert A. Chipman

#2 - *THE ENCYCLOPEDIA BRITTANICA* ...Lawrence P. Lessing

#3 - *DICTIONARY OF AMERICAN BIOGRAPHY* ...Lawrence P. Lessing

#4 - *DICTIONARY OF SCIENTIFIC BIOGRAPHY*...Charles Susskind

#5 - *WEBSTER'S AMERICAN BIOGRAPHIES*

MINIATURE BIOGRAPHY #1

by **Robert A Chipman**, *University of Toledo*

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ARMSTRONG, Edwin Howard (1890-1954), American inventor, who ranks as one of the most creative men in radio history. His principal inventions, with the years of their first patents, were the regenerative receiver (1914), the superheterodyne receiver (1920), the superregenerative receiver (1922), and wide-band FM broadcasting (1933). The invention dates in each case were a year or two earlier.

Armstrong was born in New York City on Dec. 18, 1890. When he first took up the popular hobby of wireless telegraphy at the family home in Yonkers, NY about 1908, it was common knowledge that the main barrier to progress lay in receivers. Existing types including the crystal detector and Lee De Forest's triode vacuum tube (invented 1906) all gave about the same results. Armstrong determined to invent a better one. In 1912 he achieved this goal spectacularly, using greatly improved triodes in what is now called a "positive feedback" circuit. This "regenerative" receiver earned only limited license income before World War I, but its wide use in the postwar days of amateur radio and early broadcasting made him fairly wealthy.

Armstrong graduated from Columbia University in 1913. Columbia remained his lifelong professional base, and he succeeded inventor Michael Pupin as director of electrical research there in 1935.

The superheterodyne receiver grew out of Armstrong's experience as a Signal Corps captain in Paris (1917-1919). German field-radio sets were using higher frequencies than any Allied receivers could intercept. Adapting the much earlier heterodyne invention of R. A. Fessenden, Armstrong converted the incoming high-frequency signals to a lower but "super-audible" frequency, where they could be amplified by available triodes. (The invention was first called the "super-audible heterodyne" receiver.) Although he later acknowledged inspirational help from wartime colleagues, particularly Lucian Levy of France and H. J. Round of England, the final creation was Armstrong's. It is still the most-used receiver circuit at virtually all frequencies.

Despite its impressive name, the superregenerative receiver (a spin-off from the original regenerative invention) found only limited practical use. By a quirk of market pressures, however, the sale of its rights in 1922 made Armstrong a millionaire.

The earliest nemesis of "wireless" or radio was "static" -- electrical noise of all kinds -- and its reduction or elimination was a goal of many inventors. After long experiments at Columbia, Armstrong decided around 1931 that wide-band frequency modulation offered a solution, and he obtained several patents. He spent the rest of his life proving the superiority of wide-band FM and defending his patents in a protracted struggle that used up much of his wealth. Armstrong died in New York City on Feb. 1, 1954, apparently a suicide.

The "FM" part of modern AM-FM radios, and innumerable other applications, are testimony to the superiority of Armstrong's FM. Between 1959 and 1967, his FM patents brought millions of dollars to his estate from court awards.

MINIATURE BIOGRAPHY #2

by **Lawrence P. Lessing**

Originally published in *The Encyclopedia Brittanica*

Edwin Howard Armstrong laid much of the foundation of modern radio and electronics in a series of brilliant and basic circuit designs. While still in college, he invented the regenerative circuit, which was at one and the same time the first amplifying receiver and the first reliable, continuous-wave transmitter. His most widely known circuit, invented in 1918, was the so-called superheterodyne circuit, a highly selective means of receiving, converting, and greatly amplifying very weak, high-frequency electro- magnetic waves, which today underlies 98 percent of all radio, radar, and television reception. His crown- ing achievement was the invention in 1933 of wide-band frequency modulation, which later became known as FM radio, a radical new system of nearly static-free broadcasting that transmits the full, natural frequency range of audible sound.

Armstrong's career revolved around New York City. He was born on December 18, 1890, into a genteel, devoutly Presbyterian family in the old Chelsea district of Manhatten. His father, born in the same district, was a publisher, his mother a former schoolteacher, from a neighbouring family. Armstrong was a shy boy interested from childhood in engines, railway trains, and all mechanical contraptions.

At the age of 14, fired by reading of the exploits of Guglielmo Marconi in sending the first wireless message across the Atlantic, Armstrong decided to become an inventor. He built a maze of wireless apparatus in his family's attic, by then removed to the suburbs, and began the solitary, secretive work that absorbed his life. Except for a passion for tennis, acquired from his father, and later, for fast motor cars, he developed no other interests. Wireless was then in the stage of crude spark-gap transmitters and iron-filing receivers, producing faint Morse-code signals, barely audible through tight earphones. Armstrong joined in the hunt for improved instruments. On graduating from high school, he commuted to Columbia University's School of Engineering on a red motorcycle, a graduation gift from his father, to pursue his search.

In his junior year at Columbia, Armstrong made his first, most seminal invention. Among the devices investigated for better wireless reception was the then little understood, largely unused Audion, or three-element vacuum tube, invented in 1906 by Lee De Forest, a pioneer in the development of wireless telegraphy and television. Armstrong made exhaustive measurements to find out how the tube worked and devised a circuit, called the regenerative or feedback circuit, that suddenly, in the autumn of 1912, brought in signals with a thousandfold amplification, loud enough to be heard across a room. At its highest amplification, he also discovered, the tube's circuit shifted from being a receiver to being an oscillator, or primary generator, of wireless waves. as radio-wave generator this circuit is still at the heart of all radio-television broadcasting.

Armstrong's priority was later challenged by De Forest in a monumental series of corporate patent suits, extending over 14 years, argued twice before the Supreme Court, and finally ending -- in a judicial misunderstanding of the nature of the invention -- in favour of de Forest. But the scientific community never accepted this verdict. The Institute of Radio Engineers refused to revoke an earlier gold medal awarded to Armstrong for the discovery of the feedback circuit. Later he received the Franklin Medal, highest of U.S. scientific honours, reaffirming his invention of the regenerative circuit.

This youthful invention that opened the age of electronics had profound effects on Armstrong's life. It led him, after a stint as an instructor at Columbia, into the U.S. Army Signal Corps laboratories in World War I in Paris, where he invented the superheterodyne, a circuit going far beyond the regenerative in amplification. It brought him into early association with the man destined to lead the postwar Radio Corporation of America (RCA), David Sarnoff, whose young secretary

Armstrong later married. Armstrong himself returned after the war to Columbia to become assistant to Michael Pupin, the notable physicist and inventor and his revered teacher. In this period he sold patent rights on his circuits to the major corporations, including RCA, for large sums in cash and stock. Suddenly, in the radio boom of the 1920s, he found himself a millionaire. But he continued to teach at Columbia, financing his own research, working along with Pupin, whose professorship he inherited, on the long-unsolved problem of eliminating static from radio.

In 1933 Armstrong secured four patents on advanced circuits that were to solve this last basic problem. They revealed an entirely new radio system, from transmitter to receiver. Instead of varying the amplitude or power of radio waves to carry voice or music, as in all radio before then, the new system varied or modulated the waves' frequency (number of waves per second) over a wide band of frequencies. This created a carrier wave that natural static -- an amplitude phenomenon created by electrical storms -- could not break into. As a result, FM's wide frequency range made possible the first clear, practical method of high-fidelity broadcasting.

Since the new system required a basic change in transmitters and receivers, it was not embraced with any alacrity by the established radio industry. Armstrong had to build the first full-scale FM station himself in 1939 at a cost of over $300,000 to prove its worth. He then had to develop and promote the system, sustain it through World War II (while he again turned to military research), and fight off postwar regulatory attempts to hobble FM's growth. When FM slowly established itself, Armstrong again found himself entrapped in another interminable patent suit to retain his invention. Ill and aging in 1954, with most of his wealth gone in the battle for FM, he took his own life (January 31 or February 1).

The years have brought increasing recognition of Armstrong's [place in science and invention. FM is now the preferred system in radio, the required sound channel in all television, and the dominant medium in mobile radio, microwave relay, and space-satellite communications. Posthumously, Armstrong was elected to the pantheon of electrical greats by the Union Internationale des Telecommunications, to join such figures as the French physicist and mathematician Andre-Marie Ampere; Alexander Graham Bell, the inventor of the telephone; the English electrical pioneer, Michael Faraday; and Guglielmo Marconi, the Italian inventor of wireless telegraphy.

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MINIATURE BIOGRAPHY #3

by **Lawrence P. Lessing**

Originally published in *Dictionary of American Biography*, Supplement Five, pp. 21 - 23; Charles Scribner Sons, New York.

ARMSTRONG, EDWIN HOWARD (Dec. 18, 1890 - Jan. 31, 1954), electrical engineer and inventor of three of the basic electronic circuits underlying all modern radio, radar, and television, was born in New York City, the first child of John and Emily Smith Armstrong, both native New Yorkers. His mother had been a teacher in the public schools; his father was vice president of the United States branch of the Oxford University Press. The family soon moved to the suburban town of Yonkers, N.Y., where they lived in a house on a bluff overlooking the Hudson River.

Armstrong decided to become an inventor when he was fourteen and began filling his bedroom with a clutter of homemade wireless gear. His imagination was fired by the *Boy's Book of Inventions* and by Guglielmo Marconi, who a few years before had sent the first wireless signals across the Atlantic. But wireless telegraphy was still in a primitive state. Its crude spark-gap transmitters produced electro-magnetic wave signals so weak that sunlight washed them out through most daytime hours, while its iron-filing or magnetic receivers were cruder still, requiring tight earphones and quiet rooms to catch the faint Morse code signals that were all the early wireless was capable of transmitting. As a student at Yonkers High School (1905-1910), Armstrong built an antenna mast, 125 feet tall, on the family lawn to study wireless in all its aspects. He worked with every new device that came along, among them the so-called audion tube invented in 1906 by Lee deForest. But none of the instruments were able to amplify weak signals at the receiver, nor yet to provide stronger, more reliable power at the transmitter. On graduating from high school, Armstrong began to commute by motorcycle to Columbia University's school of engineering to pursue his studies further.

While a junior at Columbia, Armstrong made his first major invention. Long analysis of the action within the audion tube suggested to him that it might be used to greater effect. The tube was based upon Thomas Edison's 1883 discovery in his early lamp of a tiny anomalous electric current that flowed across a gap from the filament to a metal plate. In 1904 an English inventor, John Ambrose Fleming, had shown that this effect could be used as a wireless receiver; two years later deForest had added a vital element, a wire grid between the filament and plate. But in the usual receiver circuit the tube did no more than detect weak signals. In the summer of 1912 Armstrong devised a new regenerative circuit in which part of the current at the plate was fed back to the grid to strengthen incoming signals. Testing this concept in his turret room in Yonkers, he began getting distant stations so loudly that they could be heard without earphones. He later found that when feedback was pushed to a high level the tube produced rapid oscillations acting as a transmitter and putting out electromagnetic waves. Thus this single circuit yielded not only the first radio amplifier but also the key to the continuous-wave transmitter that is still at the heart of all radio operations.

Armstrong received his engineering degree in 1913, filed for a patent, and returned to Columbia as an instructor and as assistant to the professor and inventor, Michael Pupin. Before his new circuit could gain wide use, however, awaiting improvements in the vacuum tube, the United States was plunged into World War I and Armstrong was commissioned as an officer in the U.S. Army Signal Corps and sent to Paris. He was assigned to detect possibly inaudible shortwave enemy communications and thereby created his second major invention. Adapting a technique called heterodyning found in early wireless, but little used, he designed a complex eight-tube receiver that in tests from the Eiffel Tower amplified weak signals to a degree previously unknown. He called this the superheterodyne circuit, and although it detected no secret enemy transmissions, it is today the basic circuit used in 98 percent of all radio and television receivers.

Armstrong returned to Columbia with the rank of major and the ribbon of France's Legion of Honor. By then, wireless was ready to erupt into radio broadcasting. In 1920, on a bid from Westinghouse Electric and Manufacturing Company, he sold rights to his two major circuits for

$ 335,000. Later he sold a lesser circuit to the newly organized Radio Corporation of America (RCA) for a large block of stock. Upon the success of early radio broadcasting, he became a millionaire, but he continued at Columbia University as a professor and eventual successor to Pupin. After a celebratory trip to Paris, he returned to court Marion MacInnes, secretary to the president of RCA, David Sarnoff. On Dec. 1, 1923 they were married.

As the 1920's wore on, Armstrong found himself enmeshed in a corporate war to control radio patents. His basic feedback patent had been issued on Oct. 6, 1914. Nearly a year later deForest filed for a patent on the same invention, which he sold with all audion rights to the American Telephone and Telegraph Company (AT & T). As radio began to boom, AT & T mounted a broad attack to overturn Armstrong's patent in favor of deForest's. The battle went through a dozen courts between 1922 and 1934. Armstrong, backed by Westinghouse and RCA, won the first round, lost a second, was stalemated in a third, and finally, in a last-ditch stand before the Supreme Court, lost again through a judicial misunderstanding of the technical facts.

The technical fraternity refused to accept the final verdict. The Institute of Radio Engineers, which in 1918 had awarded Armstrong its first Medal of Honor for the invention, refused in a dramatic meeting to take back the medal. And the action was reaffirmed in 1941 when the Franklin Institute, weighing all the evidence, gave Armstrong the highest honor in U.S. science, the Franklin Medal.

Throughout this ordeal Armstrong doggedly continued to pursue his research. He had early set out to eliminate the last big problems of radio static. Radio then carried the sound patterns by varying, or modulating, the amplitude (power) of its carrier wave at a fixed frequency (wavelength) -- a system easily and noisily broken into by such amplitude phenomena as electrical storms. By the late 1920's Armstrong had decided that the only solution was to design an entirely new system, in which the carrier-wave frequency would be modulated, while its amplitude was held constant. Undeterred by current opinion -- which held that this method was useless for communications -- Armstrong in 1933 brought forth a wide-band frequency modulation (FM) system that in field tests gave clear reception through the most violent storms and, as a dividend, offered the highest fidelity sound yet heard in radio.

But in the depressed 1930's the major radio industry was in no mood to take on a new system requiring basic changes in both transmitters and receivers. Armstrong found himself balked on almost every side. It took him until 1940 to get a permit for the first FM station, erected on the Hudson River Palisades, and it was another two years before the Federal Communications Commission granted him a few frequency allocations.

When, after a hiatus caused by World War II, FM broadcasting began to expand, Armstrong again found himself impeded by the FCC, which ordered FM into a new frequency band at limited power, and challenged by a coterie of corporations on the basic rights to his invention. Facing another long legal battle, ill and nearly drained of his resources, Armstrong committed suicide on the night of Jan. 31, 1954, by jumping from his apartment window high in New York's River House. Ultimately his widow, pressing twenty-one infringement suits against as many companies, won some $10 million in damages. By the late 1960's, FM was clearly established as the superior system. Nearly 2,000 FM stations spread across the country; a majority of all radio sets sold are FM; all microwave relay links are FM; and FM is the accepted system in all space communications.

Armstrong was posthumously elected to the roster of electrical "greats" to stand beside such figures as Alexander Graham Bell, Marconi, and Pupin, by the International Telecommunications Union in Geneva. He was the great prose master of electronic circuitry, weaving its phrases and components into magical new forms and meanings.

[The Armstrong Memorial Research Foundation, Columbia University, has files of Armstrong data, clippings, legal transcripts, personal papers, publications, photographs, and memorabilia. The papers reporting his three most important inventions are his "Some Recent Developments in the Audion Receiver," *Proceedings of the Institute of Radio Engineers*(Sept. 1915): "A New Method of Receiving Weak Signals for Short Waves," *Proceedings of The Radio Club of America* (Dec. 1919); and "A Method of Reducing Disturbances in Radio Signaling by a System of Frequency Modulation," *Proceedings of the Institute of Radio Engineers* (May 1936), reprinted in Jacob Klapper, ed., *Selected Papers on Frequency Modulation* (1970). The only full biography of Armstrong is Lawrence Lessing, *Man of High Fidelity: Edwin Howard Armstrong* (1956; rev. paperback ed. 1969). See also W. Rupert Maclaurin, *Invention and Innovation in the Radio Industry* (1949), a detailed study of early radio inventors and the patent war; the Franklin Institute of the State of Pennsylvania for the Promotion of the Mechanic Arts, Committee on Science and the Arts, Report no. 3087, Jan. 8, 1941; and obituary notice in the *New York Times*, Feb. 2, 1954.]

MINIATURE BIOGRAPHY #4

by Charles Susskind

Originally published in *The Dictionary of Scientific Biography*, Vol. 1, pp. 287 - 288, Charles Scribners Sons, New York.

Edwin Howard Armstrong (*b.* New York, N.Y., 18 December 1890; *d.* New York, 1 February 1954), *radio engineering.*

Armstrong's father, John Armstrong was a publisher who became vice president in charge of the American branch of Oxford University Press; his mother, Emily Smith, graduated from Hunter College and taught for ten years in New York public schools before her marriage in 1888. When Armstrong was twelve, the family moved to Yonkers, New york, where he attended high school and became interested in radiotelegraphy. He entered Columbia University at nineteen and studied electrical engineering under Michael Idvorsky Pupin, the inventor of the Pupin loading coil used in long-distance telegraphy and telephony, graduating in 1913.

While still an undergraduate, Armstrong made the first of his many inventions, one of the four that proved to be particularly significant: the triode feedback (regenerative) circuit. That invention, and the negative-bias grid circuit invented by Frderick Lowenstein, ultimately led to wide utilization of the as yet little-exploited triode (invented in 1906 by Lee De Forest), but Armstrong became embroiled in patent litigation and received only modest royalties.

In 1917, after serving as an assistant at Columbia for some years, Armstrong became a U.S. Army Signal Corps officer when the United States entered World War I. He was sent to France and while there developed his second important invention, the superheterodyne circuit, an improvement on the heterodyne circuit that was invented in 1905 by Reginald Aubrey Fessenden. In the heterodyne circuit, the received circuit is mixed with a locally generated signal to produce an audible "beat" note at a frequency equal to the difference between those of the two signals; Armstrong's method, which greatly improved the sensitivity and stability of radio receivers extended the technique to much higher frequencies and shifted the beat note above the audible range.

Upon returning to America, Armstrong was once again beset by patent interference proceedings, although his personal fortunes took a turn for the better: he sold his feedback and superheterodyne patents to Westinghouse Electric & Manufacturing Company (retaining royalty-earning licensing rights for the use of amateurs); he resumed his position at Columbia University; and he married Marion MacInnis, secretary to David Sarnoff, then general manager of the Radio Corporation of America.

In 1921, Armstrong made his third important discovery,superregeneration -- a method of overcoming the regenerative receiver's principal limitation: the tendency to burst into oscillations just as the point of maximum amplification was reached. RCA purchased the patents, but it did not yield the company much in royalties, since it was unsuited for broadcast receivers; it did not come into its own until special applications were developed many years later. However, RCA profited greatly from the "superhet," to which it had acquired rights through a cross licenser with Westinghouse. Armstrong found himself a millionaire.

The next decade of his life was marred by the long battle with De Forest over the feedback patents. The case was taken to the U.S. Supreme Court but Armstrong lost on a technicality. Before that decision had been handed down, however, Armstrong had completed and patented his greatest invention, frequency modulation (FM). Once again he was beset by difficulties: the U.S. radio industry resisted the introduction of FM broadcasting, FM production was interrupted when the United States entered World War II, and the Federal Communications Commission dealt FM a stunning blow in 1945 when it relegated it to a new frequency band and put restrictions on transmitter power, thus making over fifty existing transmitters and half a million receivers obsolete. At the same time, FM came to be widely used in military and other mobile communications, radar, telemetering, and the audio portion of television; but widespread adoption of FM broadcasting came only after Armstrong's death. Exhausted by a five-year suit for patent infringement against RCA and almost destitute as his FM patents began to expire, Armstrong committed suicide in 1954.

He had received many honors, including the highest awards of the two U.S. electrical engineering societies, the American Institute of Electrical Engineers (Edison Medal, 1942) and the Institute of Radio Engineers (Medal of Honor, 1918, reaffirmed in 1934 when he tried to return it after losing his legal fight against De Forest); the Franklin Medal (1941); and, for his war work, the U.S. Medal for Merit (1945). No inventor contributed more profoundly to the art of electronic communication. Armstrong is one of the two dozen honored in the Pantheon of the International Telecommunications Union in Geneva.

BIBLIOGRAPHY

Armstrong received forty-two patents and wrote twenty-six papers; the papers are listed in his biography by Lawrence Lessing, *Man of High Fidelity* (Philadelphia, 1956). See also obituaries in *New York Times* (2 Feb. 1954) p. 27; and in *Proceedings of the Institute of Radio Engineers*, 42 (1954), 635.

MINIATURE BIOGRAPHY #5

Originally published in *Webster's American Biographies*, 1974; G.& C. Merriam Company, Springfield, MA.

Edwin Howard Armstrong (1890-1954), engineer and inventor. Born in New York City on December 18, 1890, Armstrong was educated at Columbia University and before his graduation in 1913 had invented the regenerative or feedback circuit that virtually revolutionized the then still primitive field of radio. Similar and nearly simultaneous work by Lee De Forest and Irving Langmuir in the United States and Alexander Meissner in Germany led to patent litigation that was not settled until 1934, when in spite of Armstrong's apparent priority the Supreme Court decided the legal issue in favor of De Forest. After graduating, Armstrong remained at Columbia as an assistant to Michael Pupin. During World War I he served as a major in the Army Signal Corps in France and developed the superheterodyne circuit that greatly increased the selectivity and sensitivity of radio receivers over a wide band of frequencies and became the basic design for amplitude modulation (AM) radios. Returning to Columbia after the war, he went on to develop in 1920 the superregenerative circuit that came into wide use in short-wave police and amateur radio. In 1934 he assumed the professorship of electrical engineering vacated in 1931 by Pupin's retirement and held the chair for the rest of his life. Armstrong's greatest achievement was the result of several years of experimentation: in 1933 he demonstrated his system of frequency modulation (FM) radio transmission that completely eliminated static interference and that, by using a wider band than AM, made possible extremely high-fidelity broadcasts. It was six years before FM receivers were commercially available, by which time Armstrong had lost patience with the radio industry's slowness in exploiting the new medium and had built his own broadcasting station on the New Jersey Palisades. Much of his time in his remaining years was spent in litigation -- with the Federal Communications Commission over licensing for FM stations, and with various companies in the industry over patent questions. His last major contribution to radio was a method of broadcasting more than one FM program on the same frequency, the multiplexing system that made possible the rental broadcast of broadcast music to stores, restaurants, and factories and, later, the broadcast of programs in stereophonic sound. Major Armstrong, as he was usually called, took his own life on February 1, 1954, in New York City.

APPENDICES

HONORS AND AWARDS

THE FRANKLIN MEDAL

THE AIEE EDISON MEDAL

WRONG ROADS AND MISSED CHANCES -- SOME RADIO HISTORY...E. H. Armstrong

EARLY RADIO INVENTIONS...G.W.O. Howe

PAPERS RELATING TO EDWIN HOWARD ARMSTRONG

THE PAPERS OF EDWIN HOWARD ARMSTRONG...Lawrence Lessing

UNITED STATES PATENTS GRANTED TO EDWIN HOWARD ARMSTRONG

TWO RICH MINDS -- ONE POOR INVENTION...William E. Denk

ADDRESS AT ARMSTRONG MEMORIAL RESEARCH DINNER...Frank A. Gunther

A DISCUSSION OF L.P. LESSING'S UNUSUAL BIOGRAPHY...Capt. Pierre Boucheron

THE END OF KE2XCC...John Crosby

HOW DID EDWIN HOWARD ARMSTRONG DIE?...Francis H. Shepard, Jr.

OBITUARY...*New York Times*

TELEVISION IN REVIEW...Jack Gould

OBITUARY...*Wireless Engineer*

OBITUARY...*Proceedings of the I.R.E.*

CONDOLENCES TO MRS. E.H. ARMSTRONG

PRAYER READ AT CLUB'S 1954 ANNUAL MEETING

EDWIN HOWARD ARMSTRONG

HONORS AND AWARDS

Degree of Doctor of Scienc -- Columbia	1929
-- Muhlenberg	1941
-- L‘Universitè Laval (Quebec)	1948
Medal of Honor, Institute of Radio Engineers	1917
Chevalier de la Legion d'Honneur	1919
"Armstrong Medal" established by The Radio Club of America	1935
Egleston Medal, Columbia University	1939
Holley Medal, American Society of Mechanical Engineers	1940
National "Modern Pioneer Award", National Association of Manufacturers, on the 150th Anniversary of the American Patent System	1940
Medal of Class on 1989 -- School of Mines, Columbia University	1941
Franklin Medal, The Franklin Institute	1941
John Scott Medal, awarded by the Board of Directors of City Trusts, City of Philadelphia	1942
Edison Medal, American Institute of Electrical Engineers	1942
Medal for Merit (United States) with Presidential Citation	1947
Radio Club "Armstrong Medal" along with Ernest V. Amy, George E. Burghard, Minton Cronkhite, Paul F. Godley, John F. Grinan, and Walker P. Inman for the first shortwave transoceanic signals (1BCG)	1950
Washington Award, founded in 1916 by John Watson Alvord, administered by The western Society of Engineers	1951
Lion Award, awarded by Columbia university Alumni Club of New Jersey, (Essex County)	1953
Honorary Membership -- Institution of Radio Engineers, Australia	
Honorary Membership -- Franklin Institute	
Honorary Membership -- American Institute of Electrical Engineers	

THE FRANKLIN INSTITUTE

OF THE

STATE OF PENNSYLVANIA

FOR THE PROMOTION OF THE MECHANIC ARTS

AWARDS

THE FRANKLIN MEDAL

TO

EDWIN HOWARD ARMSTRONG

IN RECOGNITION OF HIS PIONEER WORK IN REGENERATION AND THE OSCILLATING VACUUM TUBE CIRCUITS; IN THE INVENTION OF THE SUPERHETERODYNE CIRCUIT; THE SUPERREGENERATOR; AND A SYSTEM OF WIDE-SWING FREQUENCY MODULATION: EACH AN OUTSTANDING CONTRIBUTION TO THE COMMUNICATION ART.

PHILADELPHIA, PA.
MAY 21, 1941

Philip C. Staples
PRESIDENT.

Harry Butler Allen
SECRETARY.

Coleman Sellers 3rd
CHAIRMAN OF THE COMMITTEE
ON SCIENCE AND THE ARTS.

THE FRANKLIN INSTITUTE OF THE STATE OF PENNSYLVANIA

FOR THE PROMOTION OF THE MECHANICAL ARTS

Hall of the Institute
Philadelphia, January 8, 1941

Committee on Science and
the Arts Case No. 3087.

The Franklin Institute of the State on Pennsylvania, acting through its Committee on Science and the Arts, has considered carefully the work of those who have contributed greatly to the advancement of science and to the application of physical science to industry, and has selected as the recipient of the award of the Franklin Medal for 1941 -

EDWIN HOWARD ARMSTRONG
of New York City, New York

The award to Dr. Armstrong is-

In recognition of his pioneer work in Regeneration and the Oscillating Vacuum Tube Circuits, in the invention of the Superheterodyne Circuit, the Superregenerator, and a system of Wide-Swing Frequency Modulation, each an outstanding contribution to the communication art.

For clarity, the outstanding radio inventions of Edwin H. Armstrong, four in number, will be discussed individually, in chronological order. There follows:

Part I. Regenerative and Oscillatory Vacuum Tube Circuits.
Part II. The Superheterodyne.
Part III. The Superregenerator.
Part IV. Frequency Modulation System.

PART I.

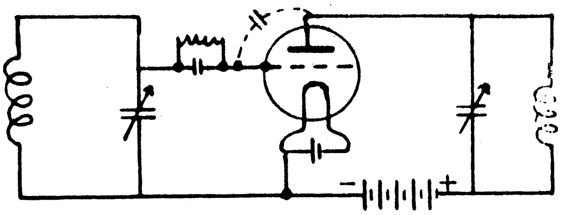
REGENERATIVE AND OSCILLATORY VACUUM TUBE CIRCUITS

In the early days of the development of radio communication two of the principal problems were the generation of sustained electrical oscillations and the control, or modulation, of these oscillations for the purpose of radio telephony. Many attempts were made by Marconi, Fessenden and others to solve these problems, without much success. The apparatus was unwieldy, complicated and difficult to maintain. The invention of the 3-electrode vacuum tube in 1907 by deForest opened the way for a solution. DeForest showed that his tube could not only be used as a detector of electrical oscillations but could also be used as an amplifier.

Armstrong, who was then a student at Columbia University, set out to study the amplification process in the vacuum tube circuit. With the collaboration of the late Professor J. H. Morecroft, he applied the oscillograph to the investigation of the nature of the currents and voltages in the audion circuit. Upon finding alternating current components in the plate circuit, he reasoned that these could be augmented by tuning, which was a general technique in radio frequency circuits. Upon inserting a tuning coil in the plate circuit, he discovered that the amplification was enormously improved and could be increased to the point where a continuous oscillation in the circuit was obtained. This, briefly, is the story of the discovery of the principle of regeneration and oscillation in vacuum tube circuits.

Armstrong's important discovery and an account of his oscillographic investigations were published in the *ELECTRICAL WORLD*, December 12, 1914. It should be mentioned that, independent of Armstrong, a number of other workers were getting results of the same general nature. These are described in the patent literature. Armstrong's invention is covered by United States patent 1,113,149, filed October 29, 1913, and issued October, 1914. Workers on this same problem at about this same time were an Englishman, H.J. Round, a German, A. Meissner, and the celebrated American physicist, Irving Langmuir. In addition, deForest had accidentally made the discovery that oscillations could be produced with the aid of the vacuum tube. This simultaneity of invention led to a long series of patent interferences and to a bitter legal controversy which was finally decided by the Supreme Court in favor of deForest, much to the astonishment of radio engineers. DeForest had been trying to use his audion as a telephone repeater and the oscillations produced a howl, which rendered his circuits useless for this purpose. He, therefore, set out to get rid of the oscillations, whereas Armstrong had found out how to put them to good use. It is generally conceded by the radio engineering fraternity that deForest was endeavoring to suppress the unwanted oscillations which occurred in his apparatus while Armstrong, understanding the nature of the phenomena, was working to control and make use of these continuous oscillations. This view was reflected in the presentation to Armstrong in 1918 of the first Medal of Honor by the Institute of Radio Engineers. When the final decision of the Supreme Court was handed down, Armstrong, in 1934, returned the Medal to the Institute. The Institute thereupon gave it back to him, reaffirming the award and indicating their conviction of his priority of invention.

The regenerative principle may be briefly described, with Plate I, as follows: A weak incoming signal which is to be amplified is applied to the control or input circuit of the vacuum tube. Since the vacuum tube acts as an amplifier, a magnified copy of this signal is produced in its plate circuit. If a part of these amplified oscillations is brought back to the input circuit and added to the original oscillations a further increase in the output is obtained. It follows that the value of the positive resistance of a circuit can be reduced or even made negative by increasing the amount of energy fed back. This regenerative process is stable provided the amount of feedback is carefully limited. If, however, this is increased above a certain point at which maximum regenerated signals are obtained, the system starts to self-oscillate and builds up a steady state which depends on the losses in the circuit and other factors, and, incidentally, the tone of the received signal is lost.



Circuit of Oscillating Audion

S. & A. Case No. 3080
Work of E.H. Armstrong. Plate 1

PLATE I.

The frequency of oscillations generated by a vacuum tube can be regulated by proper choice of the inductance and capacity in the circuit. Various methods of feeding back the energy from plate to grid can be employed and various arrangements are described in Armstrong's patent, cited above, and in an article entitled "Some Recent Developments in the Audion Receiver," *Proceedings of the Institute of Radio Engineers* 1915, pp 215 - 239.

The use of regenerative reception was wide-spread until about 1922, when neutralized circuits came into vogue. It is used very infrequently at the present time. However, the invention of the oscillating circuit was one of the greatest achievements in the art. It has revolutionized the method of generating continuous oscillations. It is used in all forms of modern radio communication. This invention alone would entitle Armstrong to a place with the greatest inventors and benefactors of the art.

PART II.

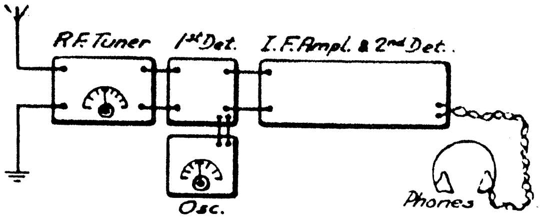
THE SUPERHETERODYNE

The Superheterodyne method for the reception of radio signals was devised by Edwin H. Armstrong in 1918. At that time he was a Captain (later Major) in the Army Signal Corps assigned to the development laboratory at Paris, France. This new type of receiver was his answer to a problem which had received the concentrated attention of a number of scientists, all seeking a radio receiver which would meet these requirements: (a) greater sensitivity than was then available, (b) usefulness at the higher frequencies (of the order of 1 MHz), (c) tunableness over wide frequency bands, (d) stability, together with (e) simplicity of control.

This type of receiver was urgently needed not only to carry on our Army's communications but to detect, over long distances, the enemies' high-frequency signals. The only sensitive receiver at this time consisted of cascaded stages of radio frequency amplifiers. If, for efficiency, each stage was tuned, forming a multistage tuned r.f. ampifier, the multiplicity of tuning condensers restricted the frequency range and the portability. Latour in France and Round in England succeeded in devising amplifiers with a maximum of 3 stages, which would operate, to some extent, at frequencies as high as 1 Mhz. These were unstable, inflexible and, with the vacuum tubes then available, gave low amplification at the higher frequencies.

Realizing that these limitations accompanied t.r.f. (tuned radio frequency) receivers, Armstrong solved the problem by discarding these and building a sensitive, stable, high-gain, low-frequency amplifier of fixed tuning, employing components and techniques that were well known. He then, by using the heterodyne principle of Fessenden, converted the incoming high frequency signals to the relatively low frequency to which his amplifier was tuned. See Plate II.

A simple example as to how this functions follows: If the amplifier (referred to as the intermediate frequency or i.f. amplifier) was adjusted to operate at 50 kHz and the incoming signal had a frequency of 1000 kHz, then a variable frequency beating oscillator in the receiver would be adjusted to a frequency of, say, 770 kHz. The voltage from this local oscillator and that from the incoming signal would be mixed in the first detector so as to produce beats, which would be the sum and difference frequencies, 1770 kHz and 30 kHz.



Schematic Diagram of
Superheterodyne Receiver

S. & A. Case No. 3080
Work of E. H. Armstrong. Plate II

PLATE II.

The lower beat frequency (30 kHz) coinciding with that to which the i.f. amplifier had been tuned would be amplified by it several thousandfold. This signal could then be detected by a second detector so that the desired audio signal would appear at the receiver's output. Of course, this could be still further amplified by means of well-known audio amplifiers.

This ingenious receiver was called by Armstrong the superheterodyne. It possesses these advantages: (a) It is sensitive. (b) It is simple to operate (there are only two receiver tuning controls.) (c) It is uniformly sensitive even for high frequency signals. (d) The final audio signal retains its original characteristics, such as timbre. (e) Its selectivity can be controlled by the shape of the overall frequency characteristic of the i.f. amplifier. (f) It is stable.

Major Armstrong applied for a patent covering his invention, dated at Paris, France, December 30, 1918, filed February 8, 1919, on which United States patent 1,342,885 was issued June 8, 1920. Claim #2 of this patent is as follows:

> "2. The method of amplifying and receiving high frequency electrical oscillatory energy which comprises, combining the incoming energy with locally generated high frequency continuous electrical oscillations of a frequency differing from said incoming energy by a third readily-amplifiable high frequency, rectifying the combined energy to produce said readily-amplifiable high frequency oscillations, amplifying the said third high frequency oscillations, and detecting and indicating the resulting amplified oscillations."

For completeness, the work of contemporaries, which occasioned some patent interference, is mentioned. The result of these actions did not perceptibly modify the original claim of the inventor. Lucien Levy of France, Walter Schottky of Germany and Lloyd Espenschied of the United States all devised systems having some general resemblance to the conception of Armstrong. An examination of these confirmed the final opinion of the United States Patent Office that they really do not constitute an interference. The evidence clearly indicates that Armstrong understood the difficult problem and its pitfalls. His solution resulted in the invention of a most valuable contribution to the art of communication -- the Superheterodyne circuit, which is found in about 98% of the millions of broadcast receivers in use today.

PART III.

SUPERREGENERATION

In 1922 Armstrong presented before the Institute of Radio Engineers a paper entitled "Some Recent Developments of Regenerative Circuits." This paper, which appeared in the August 1922 issue of the *Proceedings of the Institute*, was the first publication of his superregenerative method of reception. He was granted his first patent on the system in July 1922 (#1,424,065) and since then six additional patents on superregeneration have been issued to him. The paper describes methods by which the effective resistance of a regenerative circuit may be made periodically positive and negative, though predominantly positive.

Oscillatory circuits consisting of inductance and capacitance have a certain amount of resistance -- positive resistance. This is the reason why free electrical oscillations in such circuits are damped. When such a circuit is connected to a regenerative vacuum tube, the feeding-back energy from the tube's output to its input circuit will effectively wipe out the positive resistance of the oscillatory circuit. When the resistance changes from positive to negative, due to the feeding-back of more and more energy, the circuit becomes self-oscillatory, as previously described.

In working with his regenerative receiver, Armstrong (and hundreds of other researchers) long wished for a means still further to increase the remarkable gain in weak signal amplification afforded by regeneration. But when regeneration in a radio receiver is pushed a little too far, the tube bursts into oscillation and the tone of the received signal (whether speech or code) is lost. To pass over this "boundary line", which for years had stopped all experimenters in this field, Armstrong invented the Superregenerator.

This consisted of a receiver circuit, shown in Plate III, tuned to the weak incoming signal, connected to a regenerative vacuum tube. In this case regeneration is purposely pushed too far so that if additional means were not provided, this tube would oscillate steadily, producing annoying whistles and beat notes. To overcome this and to reproduce clear signals, a second tube, called a "quenching tube", is employed. This tube, oscillating steadily at a frequency above audibility, say 20,000 Hz per second, is connected so as to inject a positive resistance into the receiving circuit at a rate of 20,000 times a second. Thus, periodically, the signal in the r.f. circuit is permitted to build up, by regeneration, in a circuit having negative resistance. It continues almost to steady-state oscillation, only to be "quenched" by injected positive resistance and then allowed to build up again and so on. The result is tremendous amplification of signal; far beyond the "border line" at which ordinary regenerative reception was forced to stop.

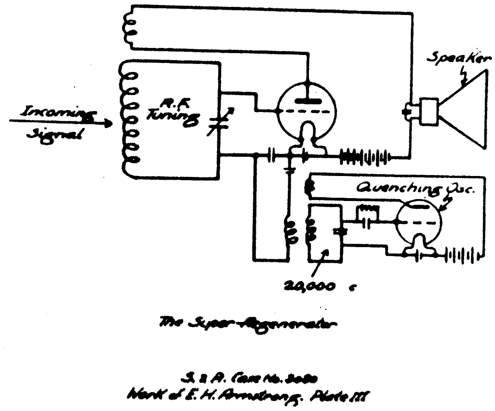


PLATE III.

To take an example: The reception at loud-speaker volume of very weak broadcast signals on, say 800 kHz, is desired, using a small receiver of only two tubes. It would be necessary to utilize the superregenerative principle. No other means is known which would permit reception with only two tubes. The weak incoming signals appear in the resonant receiver circuit tuned to 600 kHz. These signals, finding the circuit's positive resistance has been reduced to zero (or even made negative) instantaneously, by regeneration, rapidly builds up to a large amplitude (which corresponds to an amplification of many thousandfold), but before the point of steady oscillation is reached the quenching tube causes sufficient positive resistance to be added momentarily to the signal circuit to temporarily quench its oscillatory possibilities. Of course, this momentarily decreases the amplification also. It is interesting to note that such interruptions occurring at a rate above audibility do not, in a way, detract from the quality of the received speech nor is the process detected by the ear. The net result is a superregenerative receiver using a minimum of equipment, having extreme sensitivity resulting from its tremendous amplification. The disadvantages are critical adjustment, lack of selectivity and often the radiation of interference to others while receiving.

As Armstrong points out in his paper, the amplification varies more or less as the square of the ratio of signaling to quenching frequency, hence this novel circuit is used mostly for the reception of ultra high frequencies in the 50 to 100 MHz band, by amateurs and others desiring light weight, portable equipment. Probably the day will come when the method of fully utilizing this intriguing radio invention will be found -- opening a new approach to simple, low-cost radio reception.

PART IV.

FREQUENCY MODULATION SYSTEM

The flight of science against radio communication's greatest foe -- "Static" -- began years ago; in fact, almost as soon as this means of communication was initiated. The fight has continued for more than three decades. Many scientists have given up in despair, pointing out that, since the radio waves set up by electrical disturbances were of the same character as those from the transmitter, it was impossible for the receiver to differentiate between them and remain unresponsive to static while reproducing signals. Armstrong spent several years on this problem before he evolved a method that led to success. And success lay in transmitting and receiving a type of signal that possessed characteristics which *differed* from static -- which is an amplitude-modulated, impulsive wave.

Ten patents were granted Armstrong on Frequency Modulation Systems.

The type of modulation universally used at the transmitter at that time was called Amplitude Modulation. By this is meant that the "carrier", or radio-frequency, wave generated at the sender is molded, or modulated, by the information-bearing, speech-frequency wave, in such a manner that the amplitude of the carrier varies with the intensity of the impressed speech frequency. See Plate IV. Contrast this with what is known as Frequency Modulation, shown in the lower portion of Plate IV. Here the amplitude of the carrier wave remains constant and the speech frequencies cause its *frequency* to vary about a non-signaling, mid-point value.

The magnitude of the momentary frequency swing is dependent upon the intensity of the modulating sound at the moment. Frequency modulation was not new. It had been tried several years before by various researchers, thinking, incorrectly, that it would permit more transmitters to be forced into a given frequency band without interference.[1] Armstrong revived and modified this form of modulation and with new devices added at the receiver, achieved the invention of a system which may revolutionize radio communication.

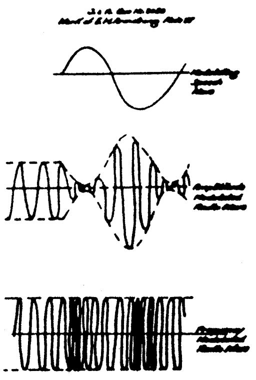
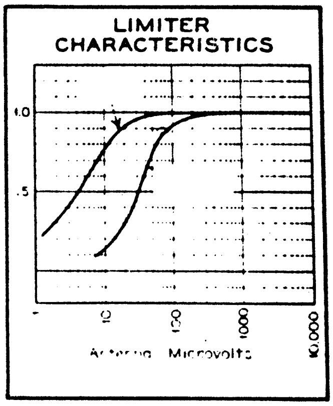


PLATE IV.

The name of the new system is the Armstrong Frequency Modulation System, usually referred to as "FM". His contribution at the transmitter was the idea of *wide-swing* frequency modulation; utilizing considerably wider swings than were previously employed when the object was merely the transmission of intelligence by means of frequency modulation. Professor Armstrong reasoned that the frequency swing due to speech currents should be several times that which would result from any disturbance. This permitted him to invent, at the receiver, means for removing the effect of electrical disturbances while faithfully reproducing the speech signals. The ordinary radio listener who enjoys F-M (frequency modulation) reception for the first time is amazed at the improvement in reproduction due partly to the single advantage of the elimination of background noise. Music stands out in its true beauty when listened to against a background of velvety silence.

Before proceeding to the receiving equipment, it should be pointed out that the apparatus to produce FM is the subject of some of the patents issued to Armstrong. Some large manufacturers of radio transmitters are manufacturing under these patents. However, at least one other method has been worked out by experimenters to give frequency modulation. It is, of course, the invention of a *system* which affords freedom from extraneous disturbances that is of prime importance, rather than the method of necessary apparatus design.

What means is included in the receiver to render it unresponsive to static? Two devices, one a "limiter", the other a "frequency detector", not found in the ordinary amplitude modulation receiver are used. These, taken together, are referred to as the Discriminator. These devices are inserted between the intermediate-frequency amplifier and the input to the audio amplifier in the well-known layout of the ordinary superheterodyne type of broadcast receiver. Thus the incoming FM signal reaching the antenna is amplified in the usual manner by the radio amplifier and passed on to the frequency-converter (or first detector-oscillator combination), then to the intermediate-frequency amplifier and hence to the "limiter". The function of the limiter tube is to smooth out any amplitude variations before the signal is applied to the frequency detector so that the signal is strictly constant-amplitude, variable-frequency. This effectively irons out noise components which are primarily amplitude variations.



S. & A. Case No. 3080
Work of E. H. Armstrong. Plate V

PLATE V.

In radio, a "limiter" is generally some form of voltage or current-operated device, adjusted so that, above a certain operating point, an increase in input produces *NO* increase in output. The characteristic curve is shown in Plate V. The limiter current in a practical FM receiver is shown in Plate VI. Notice that full limiter action is not obtained with signals weaker than 60 microvolts, indicating that for best FM reception a moderately strong signal is desirable. Limiting is secured by operating the vacuum tube (a 6SJ7) with zero grid bias and with 300,000 ohms in the grid circuit.

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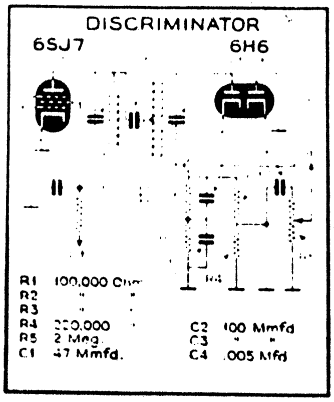
[1] Report of Committee on Science and the Arts on Work of John R. Carson.

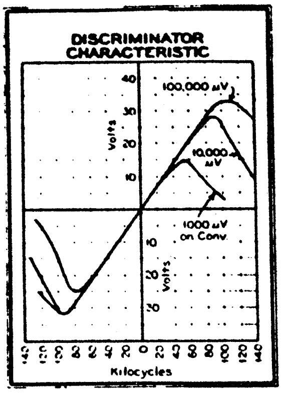


S. & A. Case No. 3080
Work of E. H. Armstrong. Plate VI

PLATE VI.

The limiter feeds its output of variable-frequency voltage to the "frequency-detector", so called because it does not function as the usual detector, although it incorporates the action of an AM detector. It consists, as shown in Plate VI, of a double-tuned i.f. transformer, the center of the secondary of which is returned to the plate of the preceding tube through a coupling condenser. A double-diode tube is connected to the extremities of the secondary with a balanced load connected between the two cathodes, one extremity being grounded. This is the arrangement of apparatus that makes it possible for us to recover through demodulation the speech voltages that have been transmitted by FM.

An examination of the mode of operation follows. (Refer to Plate VI.) The tuning and coupling of the i.f. transformer is such as to produce the well-known double-peak resonance curve. The peaks occur, evenly spaced, on either side of the non-signaling mid-frequency. Now, when the incoming frequency is swung to-and-fro, by modulation, between these two peaks, a voltage is developed, which, when detected, yields the desired audio modulating frequency. This, appearing across R-5 is led to the audio amplifier for amplification and reproduction by the loud speaker in the ordinary manner. The discriminator's characteristic curves, given in Plate VII, indicate that the audio output is substantially linear over the operating range of frequency swing. This range is increased with stronger and stronger received signals. This forms another reason for desiring moderately strong signals for FM, because then the peaks of the audio modulation can be reproduced without distortion -- peaks such as the crash of the cymbals in the orchestra.



S. & A. Case No. 3080
Work of E. H. Armstrong. Plate VII

PLATE VII.

The principle of Armstrong's Frequency Modulation System and the operation of the equipment at the receiver have been reviewed.

As this new system of static-less broadcast is rapidly developing in America, many are attributing to it features which are not the direct result of the inventions discussed here and hence should not be included in the present consideration of the work of Edwin H. Armstrong. For instance, high-fidelity reproduction. It is true that FM brings us sounds ranging up to 15,000 Hz, whereas the ordinary receiver seldom responds above 5,000 Hz. The present broadcast band, 540 to 1500 kHz provides channels only 10,000 Hz wide for each transmitter. This limits the highest modulation frequency (without interference from neighboring stations) to 5,000 Hz.

When it became evident that for an FM transmitter the radio spectrum required was several times that of an AM station (and this is a disadvantage of the FM system), the conclusion was that FM stations would be allocated in the ultra-high frequency band -- the only available region where there was enough territory to satisfy the demands of the broadcasting stations (more than 125 in number) who, in the near future, will begin commercial broadcasting using the Armstrong system. The Federal Communications Commission has set aside the band 43 to 50 MHz for FM. At last broadcasters enjoy channels wide enough to permit the transmission of sounds up to 15,000 Hz (or higher). Receiver manufacturers are doing their part by offering receivers for FM into which have been designed circuits and loudspeakers which will produce, for instance, the upper harmonics of the violin in a manner to give true realism to the music reproduced in our homes. Professor Armstrong, in his practical development of this invention (which he had to carry on single-handed for several years before the radio world awoke to the value of FM), wisely made full use of the boon of high fidelity and guided others along this way. He, however, claims no invention in so doing.

The necessity of using ultra-high frequencies for FM broadcasting definitely limits the range of a station to its optical horizon (times a certain factor). This is another distinct disadvantage indirectly accruing to this new system, which apparently will never afford long distance reception - (except as made possible through network broadcasting). It has been found that with an antenna 400 feet above the earth, using a power of 50 KW, the distance covered is about 200 miles.

FM reception is not entirely free from electrical noise, nor is receiver distortion negligible, unless a reasonably strong signal is being received. The reason for this has been mentioned.

The ordinary broadcast receiver cannot receive FM broadcasts. The discriminator circuit shown, could be added to it, but it would be more satisfactory to install a new receiver designed for FM (and AM) reception.

Already this new method of radio communication has made possible the successful relaying by radio (not over wire lines) of broadcast programs through four, or more, stations linking New York City with various stations in New England. Such a multi-step relay system yields speech quality equal to or better than that furnished by the usual broadcasting toll wire service. The successful relaying of television pictures has also been carried out. While broadcasting an ordinary musical program, an FM station can simultaneously transmit facsimile signals by amplitude modulation. F-M greatly improves the important factor of understandability in services such as police radio, aircraft and tank corps services, and it offers millions of American listeners increased musical enjoyment. It has the features of a revolutionary improvement.

PRESENTATION OF THE MEDAL OF THE FRANKLIN INSTITUTE

Report of the Medal Day Meeting - May 21, 1941

Originally published in *The Journal of The Franklin Institute* Vol. CCXXXII Sept. 1941, pp 260 - 262

To Edwin Howard Armstrong, Sc.D.,

Professor of Electrical Engineering, Columbia University

Dr. Staples: "I now call upon Dr. A. F. Murray, sponsor of our Franklin Medallist."

Dr. Murray: "Mr. President, the Board of Managers of The Franklin Institute, upon recommendation of its Committee on Science and the Arts, unanimously voted to award a Franklin Medal to Dr. Edwin Howard Armstrong, Professor of Electrical Engineering, Columbia University, New York City, 'in recognition of his pioneer work in regeneration and the oscillating vacuum tube circuits, in the invention of the superheterodyne circuit,the super-regenerator, and a system of wide-swing frequency modulation, each an outstanding contribution to the communication art.'

"Dr. Armstrong's career as an inventor began at the early age of twenty-two. While he was a student at Columbia University, in 1912, he invented the regenerative vacuum tube circuit.

"More inventions followed -- inventions which today, in their worldwide use, overshadow, in breadth and practical importance, those of any other inventor in the radio field.

"We usually think that most great and helpful discoveries in chemistry, physics, radio and the like, come from the large, well-equipped laboratories of manufacturing companies. We note with interest, therefore, this exception. Dr. Armstrong has never been a part of the radio manufacturing industry. As a lone researcher, he has contributed such far-reaching improvements that, if these were suddenly withdrawn from us, not only would the vast radio industry itself come to an immediate halt, but radio communications throughout the world would cease and millions of listeners would be seated beside silent broadcast receivers.

"Armstrong graduated from Columbia University in 1913. During the first world war he was stationed at the United States Signal Corps Laboratories in Paris, France, as a Captain and later as a Major. Major Armstrong's contribution at this time was the superheterodyne. This not only was a great aid to the Army radio but twenty years later we find that nearly all of the radio broadcast receivers in our homes employ the superheterodyne principle.

"In 1929 he received from Columbia University a Doctor of Science degree and since 1937 he has been Professor of Electrical Engineering at Columbia.

"Professor Armstrong, to whom more than thirty-three patents have been granted, is the author of numerous technical papers and the recipient of many awards. Among these are -- the Medal of Honor of the Institute of Radio Engineers; from France, Chevalier de la Legion d'Honneur; the Egleston Medal from Columbia University; a National *Modern Pioneers* award, and the Holley Medal of the American Society of Mechanical Engineers.

"For many years, in his research laboratory, Professor Armstrong has been working on the solution of radio's 'Enemy Number One' -- that is -- Static. Three years ago he announced the solution -- a system known as 'Wide-swing Frequency Modulation.' Did the radio world embrace this new idea with open arms? No. On the contrary, the inventor himself was forced to build and operate a high-power, FM broadcasting station, and in this way initiate experimentally a new system of broadcasting in the United States. At first it grew slowly, then rapidly, until now it has reached the accepted commercial stage. Thus today we are entering a new era of broadcasting, one which will bring us increased listener enjoyment in our homes through high-fidelity, noise-free reception.

"Mr. President, I have the honor and the pleasure of presenting to you for the award of a Franklin Medal, the outstanding radio inventor, Dr. Edwin Howard Armstrong."

Dr. Staples: "Dr. Armstrong, all of us take pride in your reception of a Franklin Medal. To those of you ladies and gentlemen who have to do with the field of communications, the name of Major Armstrong is a household word; and all who have to do with communications take pride in Major Armstrong's accomplishments.

"To you, Sir, by virtue of my office as President of The Franklin Institute, I take the greatest satisfaction in presenting the report which accompanies the Medal award, the Franklin Medal, and a Certificate of Honorary Membership in The Franklin Institute."

Dr. Armstrong: "I know I should try to express how greatly I appreciate this honor which you have conferred upon me. To have had a part in the struggle which many men have waged with the effects of lightning for many years, and to receive an award bearing the name of the great philosopher who first brought it down from the clouds is indeed an honor which I shall never forget.

"But perhaps there is something that I can more fully express, regarding a new force of freedom in radio..."

THE NEW RADIO FREEDOM

by **Edwin H. Armstrong, Sc.D.**
Columbia University

Read at the Medal Day Meeting of The Franklin Institute, Wednesday, May 21, 1941, upon receiving The Franklin Medal
Originally published in *The Journal of The Franklin Institute* Vol. CCXXXII Sept. 1941, pp 213-216.

A wall which has stood for years across the line of march of radio has been broken down. We look toward a new horizon and envision a new freedom of action. For that wall which has fallen is the belief in the minds of men that nothing could be done about the problem of "static" and the cause of the removal of this wall is the discovery of a new principle in electric signaling.[1]

We now see clearly that the way to free ourselves from the effects of the various natural and man-made electrical disturbances which bedevil the present system of radio is to transmit waves whose characteristics differ in kind from those of the disturbances so that it becomes possible to distinguish at the receiver between the signaling and the unwanted kinds of waves. We see not only freedom from the distressing noises which are only too familiar to us all, but freedom from what engineers refer to as distortion and cross-modulation resulting in the unnatural reproduction of the tones of music and the human voice. Here also the new principle applies, removing the main source of this trouble and giving us a realism which can, on certain types of broadcast programs, be very startling, indeed.

The application of the principle to the interconnection of broadcasting stations by radio relay will free us from the limitations of the existing wire line system which is now in use and will extend service into regions where economics and physical obstacles do not permit it to go. The advent of an "all radio" broadcasting system is not too far away. Various applications in the field of communications for aircraft, civil emergency and the military service are now being made.

The social and political aspects are taking form, for by a combination of curious properties of the new system[2] and the propagation characteristics of a hereto unused part of the radio spectrum within which the system is now operating it becomes possible to set up many times the present number of broadcast stations. A "place on the air" hitherto denied them now becomes available for our educational and denominational institutions. Space is also is available for stations for every town and city in the country and the increase in the number of channels of communication to the listening public and the attendant problems raised thereby forecasts re-examination of past legislative acts to determine their application to and bearing upon our freedom of expression.

As we look into the future all this can be clearly seen; beyond lie the parts less clearly visible, perhaps so obscured as to be in the realm of prophecy. Precisely here is is the time to look backward; to study the teachings of the history of the art, to observe the effects of the introduction of each new principle, and above all, to compare the prophecies, (or the failure to prophesy) with what actually came to pass.

The outstanding examples are not hard to find. Turning to the early days of Marconi, we see him transmitting a distance of a few miles with the waves of Hertz, limited, as those who understood electromagnetic theory were not slow to point out, by the same laws as those which governed the transmission of light. Who could foresee that in future experiments he was to elevate one of the elements of the Hertz oscillator and ground the other, thereby attaching the waves to the surface of the earth so that the barrier of the horizon was to disappear? And who, even after the principle of Marconi's discovery became known foresaw how far the art would develop before it came upon another of the great barriers which was to check its progress for a time?

This barrier lay in the fact that the energy which created the signal in the receiving system was limited to that actually transmitted through space from the sending station. Oftentimes these signals were so faint in the then universally used telephone head set as to become discernible only through the holding of one's breath, an experience which was an every day occurrence to the experimenters of those times. The finding of a method of causing the received signal to release and to control locally created energy in any required amount some fifteen years after Marconi's discovery broke down the second barrier. This ushered in the vacuum tube or modern radio era, which was to bring transoceanic communication, a practical radio telephone, and finally broadcasting in its wake. Only the merest part of the vast development to come was forecast, and there was little appreciation that this discovery was to open up an era of inventive progress the like of which the radio art had never seen.

Who was to foresee that some dozen years later, when the art had settled down to the transmission of its overseas communication with waves many miles in length, confident that by the use of these long waves it had overcome one of its major obstacles (the inability of shorter waves to span the oceans in daylight), that a miraculous discovery was to overturn every principle of propagation the art believed in. For, by the utilization of waves shorter than any which had heretofore been employed, infinitely better daylight transmission was to be obtained over greater distances than long waves ever gave, in fact, to the ends of the earth.

Looking backward over these and other examples of the failure of the prophets to foresee what was to come leaves one with a source of wonderment at their lack of vision until one reflects that, after all, theirs was but the judgment of mortal men. So in endeavoring to appraise the present situation and in seeking to outline the extent of our travels in these newly opened fields before the next great barrier is encountered, ought we not to make our approach with profound distrust of the value of that wisdom and vision which it pleases us to think we possess?

It seems to me that he who fails to learn the lessons of the past, who fail to see that "we look backward as in the glare of a searchlight and forward through an impenetrable fog" and prefer instead to trust his present fleeting vision of what he thinks he sees is bound to misjudge the future. Would it not be better, and I call this particularly to the attention of those who are to see for the first time the results that follow inevitably from the application of new principles to an art, to be guided by the words of Owen Young spoken many years ago, "What gives me confidence in the future of radio are the things we do not know about it."

REFERENCES

[1] A Method of Reducing Disturbances by a System of Frequency Modulation. *Proceedings Institute of Radio Engineers,* May 1936.

[2] The ability to reject the weaker of two signals on the same channel.

PRESENTATION OF THE A.I.E.E. EDISON MEDAL

Originally published in *ELECTRICAL ENGINEERING*, 62 (April 1943), 147 - 151

Presentation of three of the highest engineering honors -- the Edison, John Fritz, and Hoover Medals -- to three engineers in vastly different fields of the profession, at a special session of the AIEE national technical meeting on January 27, 1943, was unique in the history of the Institute. Research has revealed that at no time previous to this have three such signal honors been conferred at one AIEE ceremony. The 1942 Edison Medal, highest award of the AIEE, was presented to Edwin Howard Armstrong, professor of electrical engineering, Columbia University, New york, N.Y. Willis R. Whitney (A '01), vice president in charge of research, General Electric Company, Schenectady, N.Y., was awarded the 1943 John Fritz Medal, given for notable scientific or industrial achievement. The award of the 1942 Hoover Medal, honoring an engineer for distinguished public service, was made to Gerard Swope, (F '22), president of the General Electric Company, New York, N.Y.

At the Awards Dinner of the American Institute of Electrical Engineers in 1942 when Armstrong (right) received the Edison Medal. With him are (left to right) Gerard Swope, the Hoover Medalist, Dr. Willis Whitney, the John Fritz Medalist.

E. H. Armstrong -- Edison Medalist

by **Alan Hazeltine, Fellow AIEE***

If we review the advances in electrical technology in the past 25 years, one development stands out from all others, electronics, and specifically the application of the three-electrode vacuum tube. It is appropriate to recall here that the original electronic tube was the two-electrode tube of Edison, in whose honor the Edison medal was established. Others subsequently applied this "Edison effect" in radio detection and introduced the control electrode, but the action was viewed as that of a trigger, as in the modern thyratron, which is of limited application. The real foundation for the unlimited development which we have witnessed was laid by the Edison Medal recipient, Doctor Edwin Howard Armstrong, in an article published in the *Electrical World* in December 1914. Here the common engineering tool, the characteristic curve, was employed for the first time to show how the tube amplifies; and the theory was substantiated by oscillograms which Armstrong had taken. The previous mysterious action of the tube as a rectifying detector with a grid capacitor was elucidated in the same way.

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*Alan Hazeltine is professor of physical mathematics at Stevens Institute of Technology, Hoboken, N.J.

I well remember the impression this article made upon me at the time, and the conviction that here was something with great possibilities. I also remember the excitement produced a few months later by Armstrong's first paper before the Institute of Radio Engineers on his feed-back circuit, which employed this theory to give undreamed-of amplification of weak radio signals and permitted the general use of heterodyne reception by providing for the first time a source of continuous oscillation of frequencies as high as any then used for radio transmission. May I take this occasion to note that these publications of Armstrong started my own work in radio and profoundly affected my subsequent career, as they have the careers of many others?

It is rather hard to take ourselves back to conditions in radio prior to Armstrong. Attempts were being made at transoceanic telegraph communications, but with only very restricted success, even with enormous receiving antennas and elaborate commercial apparatus. The radio amateurs, who shortly were to be the mainstay of Signal Corps and Navy radio in World War I and were later to supply the radio engineering talent called out by broadcasting, could receive only local signals. Armstrong's work removed the barrier to regular long-distance radio telegraphy. By increases in power of the vacuum tubes, it also provided an easily modulated high-frequency source for radiotelephone transmitting, so that long-distance radiotelephony soon followed. And then came the great broadcasting development with its far-reaching social consequences.

The early work of Armstrong, the experimental part of which was done while he was still an undergraduate at Columbia University, soon received recognition. Its importance was appreciated by Professor Pupin, who took Armstrong under his wing. Together they carried on several researches in radio. In 1917 the Institute of Radio Engineers awarded its Medal of Honor to Armstrong for the feed-back circuit, the presentation being made by Professor Pupin, then president of that society. I recall a remark of Professor Pupin on that occasion: that inventions are sometimes ascribed to luck, but that the best luck is to have a good head on one's shoulders! The correctness of Pupin's appraisal has been demonstrated amply by Armstrong's subsequent career.

In this period, the question of amplification due to heterodyne reception was in dispute. Armstrong clarified the matter in a paper presented to the Institute of Radio Engineers in 1916. Doubtless this study paved the way for Armstrong's next important invention, the superheterodyne receiver, although Armstrong himself attributes it to the luck of a chance conversation in which were pointed out the limitations to the amplification feasible at the higher frequencies. Armstrong changed the wave frequency to a lower intermediate frequency by heterodyne action, using his vacuum-tube oscillator, and then carried out further amplification at this intermediate frequency. This method was developed for military purposes during World War I, while Armstrong was an officer in the Signal Corps in France. Now it is employed almost universally in radio reception.

Armstrong never abandoned his first love, radio. After the war, he returned to his laboratory researches at Columbia; and here, in an experimental set-up for another purpose, he happened to notice an extraordinary amplification of a locally generated signal. Ninety-nine out of one hundred experimenters would have failed either to notice the effect or to find the cause. But Armstrong's characteristic persistence and ability to analyze physical phenomena tracked down the demon; and superregeneration was added to the radio art. Although it was not of such wide utility as Doctor Armstrong's other fundamental inventions, it was found essential in pioneer work at ultrahigh frequencies and now is applied to certain military purposes.

By this time, we were in the era of broadcasting. Some of the best analytical brains had been directed to the theory of radio. It seemed that all the foundations had been laid, that no new fundamental methods were to be anticipated. Frequency modulation had been considered, used to some extent, and then discarded. The fallacy of using it to narrow the band of transmitted frequencies had been exposed. It was rejected as useless and even harmful. But Armstrong had other ideas. By going contrary to accepted notions and greatly widening the range of frequency variation, he developed a system of frequency modulation ideally suited to broadcasting, which was announced only in 1936. Although facing the tremendous handicap of an established broadcasting system, with thousands of transmitting stations and many million of receivers in use, none of which could employ it, it already seemed destined largely to supplant the conventional amplitude modulation. The two great limitations in amplitude modulation were the noise accompanying the signal and the interference between stations on neighboring frequencies, so that over a large area two stations would spoil each other's programs. Wide-range frequency modulation enormously improved the signal-to-noise ratio and almost eliminated the area over which stations on neighboring frequencies would interfere. Besides, the use of ultrahigh frequencies, essential in this system, made it feasible to cover a wide audio-frequency range, with great improvement in the fidelity of reproduction.

Of course, Armstrong has made many other discoveries and inventions. Specific oscillating circuits commonly associated with other names were among those which he was the first to study. In his early work with Pupin, he considered a regenerative vacuum tube as a controllable negative resistance or reactance element; and he made laboratory measurements of these properties. But the time was not ripe for the present-day applications such as automatic tuning.

Not only has all of Armstrong's work been built on the electronic vacuum tube originating with Edison, but his most evident characteristic has been that for which Edison was famous -- pertinacity. I can testify that mealtime meant nothing to Armstrong when his mind was is set on a technical matter; this musty be settled first, even though an after-dinner discussion would have been as effective. But it is just such concentration that has been needed to carry through his discoveries and developments.

There is another characteristic of Armstrong which is not so immediately evident: He is mathematical, because all of his results, no matter how he was first led toward them, were ultimately put in logical exact form. He is not known for the discovery of new scientific facts, nor for the creation of new structures. His discoveries were methods -- new ways of doing things. Let us draw a parallel: The true father of electrical engineering was Faraday, who laid a new foundation for every branch of electrical science and whose concepts are the working tools of the electrical engineer.

Because no algebraic equations appear in Faraday's writings, he has been viewed simply as an experimental physicist. But Pupin, appreciating the exactness of Faraday's reasoning, has pronounced him a great mathematician. It is so with Armstrong, who shies when you talk to him with equations, but who reasons clearly and accurately in the many-dimensional field of physics, rather than in the one-dimensional field of algebra and calculus. It may be significant that in Pupin's old office, which Armstrong now occupies, there hangs one picture each of the two famous pioneers of electrical science, but there are two pictures of Faraday. Armstrong also is an inspired mathematician.

VAGARIES AND ELUSIVENESS OF INVENTION

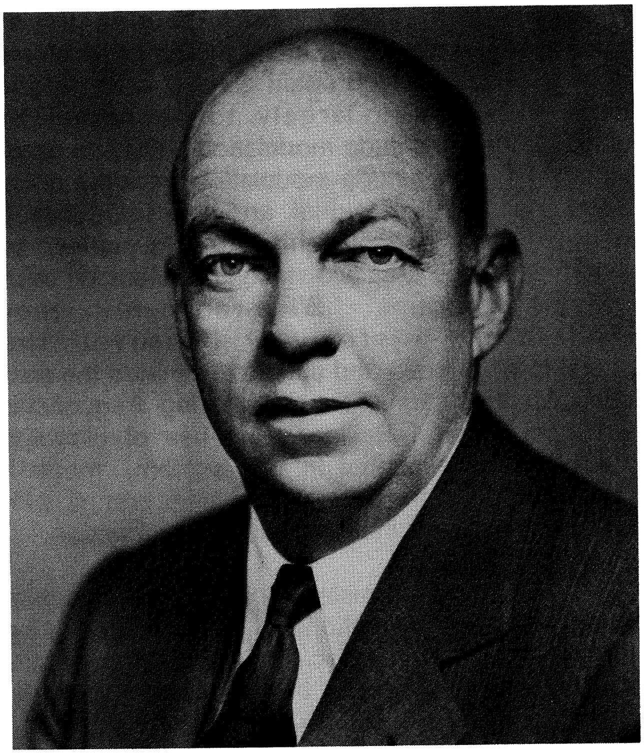
Edwin H. Armstrong

It is not possible for me to find the words to tell you what this honor means to me. To have belonged to the generation which learned the meaning of volts and amperes when Edison was at the height of his career, to be able to follow in the footsteps of my old instructor -- Michael Pupin -- who stood here 22 years ago, and to have my own work appraised, during these difficult days, as worthy of the Edison Medal, gives it an inspiring meaning that can never be described.

But on an occasion such as this, when a man looks back over the events associated with his work, there comes some sobering second thoughts. For he begins to realize how minor is that part which he himself has played in shaping the events of his career, how overpowering the part played by circumstances utterly beyond his control. The continuous good fortune which has followed me, providing second chances at inventions when the first chance was missed and tossed away, has been all that a man could hope for and more than he has any right to expect.

Only the invention of regeneration and the system of frequency modulation were the result of any conscious effort on my part to solve a definite problem. One problem was attacked on no theory at all except that something must be wrong with the existing one; the other problem was attacked by a method of reasoning that was to turn out to be just 100 percent wrong. And in each case, a chance observation in the laboratory was to lead me to the discovery of principles the existence of which I never had the remotest idea.These occurrences, however, must be considered as the outgrowth of quite ordinary and conventional research in the light of the chain of circumstances which were to lead to the discovery of the superheterodyne and superregenerative principles. One of these was to come from a war, the other from a legal proceeding.

I am most highly flattered by the reference which my good friend, Alan Hazeltine, has made to any ability of mine in the realm of the mathematical way of thinking. The fact is that the first step in the chain of events which was to lead to the superheterodyne invention came about because I could not understand the mathematics used in the dispute he has referred to, and I had to make a long experimental investigation to clear it up. This investigation gave me for the first time a clear understanding of the nature of the heterodyne. These results were published shortly before I left for France for service ion the Signal Corps in the American Expeditionary Forces.


Edwin H. Armstrong, 1942 Edison Medalist

Shipped via England, I arrived in Southampton, and there came a second link in the chain of good fortune. Bad weather was to close the English Channel for three days and give some of us the opportunity to go to London and see the town. There I chanced to meet Captain Round of the British Army Intelligence Service and from him learned of one of the most important problems of the war, the reception of very weak signals of what then were considered to be "short" wave lengths. He outlined the highly ingenious steps which already had been taken along conventional lines, but as they involved the use of special vacuum tubes which we did not have, it was clear that the problem as far as the United States forces were concerned was one for the base laboratories. The information was duly forwarded to the United States.

The third link came months later as I happened to be watching a night bombing raid and wondered at the ineffectiveness of the antiaircraft fire. I may say that night bombing was not very dangerous in those days, either for the man on the ground or the man in the airplane. Thinking of some way of improving the methods of locating the position of the airplanes, I conceived the idea that perhaps the very short waves sent out from them by the motor ignition systems might be used. The unique nature of the problem, involving the amplification of waves shorter than any ever contemplated and quite insoluble by any conventional means of reception, demanded a radical solution. All three links of the chain suddenly joined up and the superheterodyne method of amplification was practically forced into existence. Not one link in the chain could have been dispensed with. This, I think is the only completely synthetic invention I have ever made.

The superheterodyne was never used in World War I for the purpose for which it was invented. A more improved use for it then was found. But it is interesting to note that it is one of the indispensable elements of an aircraft-detection scheme of the present war which operates on a much more practical system.

Seldom can an inventor look philosophically upon the bane of his existence, patent litigation, and find much good therein. He might be expected to become philosophical about the serpent in the Garden of Eden. Yet the superregenerative circuit was to be discovered as a direct result of a legal action in which the regenerative circuit became involved shortly after World War I. During these proceedings it came to pass that counsel for the opposition made denial of some fundamental truths. Such behavior is not entirely unknown in courts presided over by even our most learned judges, nor can it be said to be entirely unsuccessful.

To furnish a convincing answer, I set up demonstration equipment involving some measurement apparatus that included a regenerative circuit. These instruments were all placed on a table in the Marcellus Hartley Research Laboratory at Columbia University and arranged to receive from a miniature transmitter across the room, and were quite disassociated from any antenna or ground connection. While I was adjusting the receiver to respond to signals from the miniature transmitter, other signals of a most unusual character suddenly came in. The first thought was that a British cruiser was nearby in the North River, since the tone of the telegraphic signal was somewhat akin to their characteristic double-tone spark note and the strength was so remarkable. It was then observed from the character of the messages that the signals were coming from the Brooklyn Navy Yard. Other well known stations also came in with a strength hundreds of times that which any regenerative circuit would give. As it gradually dawned upon me that some new principle of amplification was being observed, the nature of which I could not even guess, the effect disappeared and could not be reproduced. Only the comparatively feeble response of a simple regenerative circuit was left, and nothing I did would make it behave in other than its quite conventional manner.

Five minutes before I would have sworn to the high heavens that I understood all there was to know about regeneration. Five minutes only were required to wipe out that complacent belief engendered by nearly a decade's work with the subject. Some completely bewildered experimentation eventually restored the strange effect, and finally I learned how it could be maintained long enough to examine it. And then it only remained to find out what it was all about and discover the principle of operation. A little work brought to light a principle quite beyond the bounds of one's wildest dreams. Its existence had never been suspected, in any way and it is doubtful if it ever could have been evolved by analytical means. Professor Hazeltine, who helped me over the high spot in one of the obscure phases of this theory, will, I think, bear me out.

Much of what I have said is already well known, but there is one chapter in the history of superregeneration which has never been published. It was not known to me until a few years ago.

Five years before the events which I have just related took place, I set up and operated what I now know to have been a superregenerative circuit. Because of the particular condition under which it was used, the superregenerative effect was not manifestly outstanding. I missed it, ascribing the operation of the circuit, which was somewhat better than expected, solely to the effects of ordinary regeneration. The arrangement was published in my original paper on regeneration in 1915, described as a regenerative circuit, and the paper was translated into many languages and went to the four corners of the globe. No one apparently saw anything more in it than I. Nearly 20 years later, while looking idly through this old paper, recollections of some of the effects observed brought the startling thought that I must have then had and missed superregeneration. The original apparatus, which was still intact, was set up and put into operation again and it superregenerated beautifully! It is seldom that one avoids the penalty for a blunder such as this.

I have a story here of events that good fortune alone could bring about, but I do not want to create the impression that one's guardian angel always acts so promptly. The chance observation in the case of the frequency-modulation system was delayed for nearly 20 years while a course of what I, at least, considered reasoned effort led to a chase of more will-o-the-wisps than I ever thought could exist. It takes a long time to learn the lesson that reasoning sometimes cannot give the answer.

There has grown up through the years a school of thought that is coloring some of the recent legislative proposals dealing with invention, which holds that invention can be reduced solely to a basis of logic and reasoning. I wish I could persuade them to explain to me the system; it would save an enormous amount of trouble. I have never been able to do it, except afterward. For the disciples of that school, I would suggest just a few years apprenticeship in a laboratory, working on what we today would term an "insoluble" problem. Daily contact with the laws of nature has a way of keeping a man's feet on the ground.

I have tried to describe the effect that circumstances quite out of my control had to do with the making of these inventions. I wish it were possible to describe here also that part played by my old instructors and those who have assisted me through these years. Here also I have had extremely good fortune. For the moment I can only echo the thought expressed by the recipient of the Edison Medal last year, that he wished the names of those who had helped him attain it could also be engraved upon it, and say that whenever I look upon this award, I shall always see their names around it.

Wrong Roads and Missed Chances—Some Ancient Radio History

A pioneer in communication, a professor at Columbia University and this year's Washington Award recipient, Edwin Howard Armstrong, chose as his address a study of the background of radio and the detours radio took before it became a world-wide reality.

By **EDWIN HOWARD ARMSTRONG, 1951 Washington Award Recipient**

The art of "signaling through space without wires" has passed the half-century mark. In that period, from the transmission of Morse signals over a mile or two of level ground, at speeds of a few words per minutes, it has progressed to the transmission of sound to the ends of the earth, and it has begun the same conquest of space for sight, by means of television. The industry that has been built upon the discoveries and inventions of the period has produced an effect upon our lives that, so far as I am aware, Nikola Tesla alone had the vision to prophesy.

But as the history of the art is written down, and its different phases are seen in the perspective that the passing of time alone makes possible, one is struck by the wrong roads that have been taken, and the chances that repeatedly have been missed to get back on the right ones.

It is difficult to find the facts about events of the early days of "wireless," for the pioneers are no longer with us; we cannot ask them why they did what they did do, and not something different. For later stages of radio development we are more fortunate; there are records from which we can reconstruct the history of the wrong roads that were taken, and of how the right roads were found. Perhaps the most illuminating chapter in this history is Marconi's discovery of the daylight wave—the discovery that created world-wide radio communication as we know it today. It is from that chapter of radio history that I shall try to draw the lesson of this paper. The story begins with Marconi's much earlier discovery of the grounded wave, which started wireless communication on its course.

Marconi, when he began his search in 1895 for a practical wireless signaling system, did not at first depart from the teachings of earlier experimenters, but proceeded along conventional lines and, by exercise of great ingenuity, extended the distance over which radio waves could be detected from a few hundred feet to a matter of several miles. His expressions of hope for longer distances met adverse criticism from scientists of the day, who recognized kinship between the waves from Marconi's beam and the light waves of a searchlight, and reasoned that the horizon must be the limit of a wireless signal, as of a searchlight's rays.

Had Marconi been more of a scientist and less of a discoverer, he might have concluded that his critics were right, and stopped where he was. But like all the discoverers who have pushed forward the frontiers of human knowledge, he refused to be bound by other men's reasoning. He went on with his experiments; and he discovered how, by attaching his transmitted waves to the surface of the earth, he could prevent them from traveling in straight lines, and make them slide over the horizon so effectively that in time they joined the continents of the world. Several years were to pass before agreement was reached on the nature of Marconi's great discovery, though Marconi himself understood very well how to apply it and to employ it usefully; and it proved to be the foundation upon which the practical art of wireless signaling was built.

Marconi's claim to the invention of wireless telegraphy is beyond challenge. Resurrection of the ancient claim of Professor A. S. Popoff, Marconi's Russian contemporary, fails because Popoff's suggested transmitter did not produce the grounded wave, and his proposal for a ground connection at the receiver, without one at the transmitter, proves that he lacked a conception of the basic principle that Marconi discovered.

For twenty years the "grounded waves," christened "Marconi waves" by my old teacher, Michael Pupin, were the accepted means of all long distance signaling. But today for long distance communication we no longer use them, save for a few special purposes. They have been replaced by a newer and radically different process of projecting waves into space, free of the earth, to bounce

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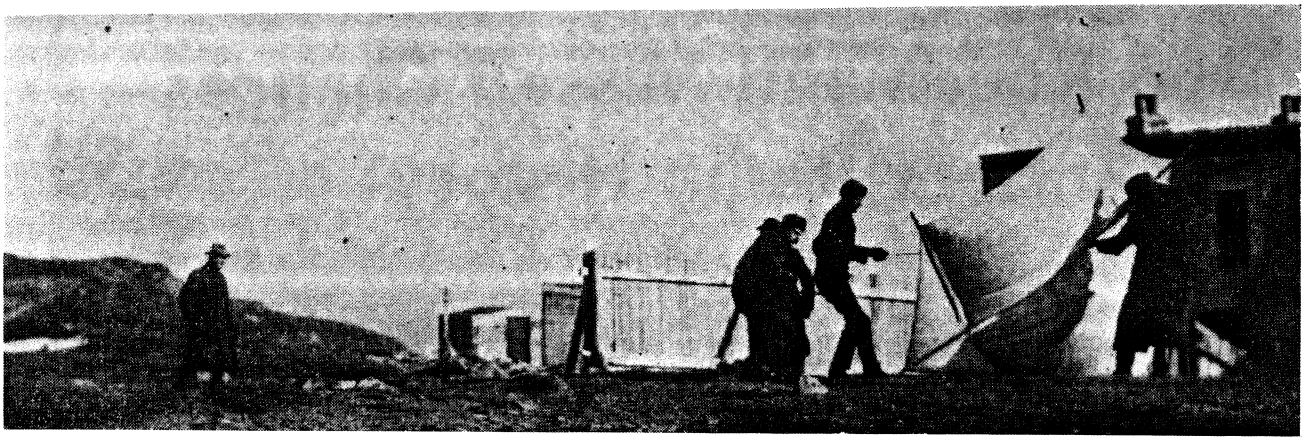

Reproduced above is a print made in 1901 at St. Johns, Newfoundland. Marconi and his associates are erecting a kite-supported antenna to receive the first trans-Atlantic radio signal sent from high-power station in England.

against an electrical ceiling 100 miles or so above the earth's surface, where they are reflected back to ground at some distant point. By a technique acquired through experience and based on the length of wave, the time of day and certain seasonal characteristics, we cause these waves to come back to earth in any desired area of reception.

Surprisingly enough it was Marconi who, more than 25 years after his original discovery, made the second great discovery that was to show that we had been on the wrong track, and to set us back on what we are presently pleased to consider the right one.

The story of how radio at the turn of the century went down what turned out to be a dead-end road, and how the right road was ultimately found, is a fascinating one. By 1900, Marconi had carried his experiments to a point where he was ready to make the great test of whether radio waves could be made to span the Atlantic. Accordingly, he built the first "high power" station in the world at Poldhu, England and went to St. Johns, Newfoundland to listen for the signal. There, in December, 1901, his bold project came to a successful conclusion when, with a kite-supported antenna, the agreed signal—the letter "S"—was occasionally detected.

We know all too little about the characteristics of the historic Poldhu transmitter, for the art of measuring wave lengths and antenna power was yet to be developed. The best present-day estimates place the wave length somewhat below 2,000 meters, and the power around 10 kilowatts. The experiment evidently showed Marconi that the gap between an occasional signal and regular transoceanic communication would be a large one, and that much more knowledge of the propagation of radio waves would have to be obtained.

In the following year, 1902, experiments conducted between the Poldhu transmitter and receiving equipment on the "S. S. Philadelphia" uncovered a new phenomenon—that Marconi's waves travelled better at night than by day. Various hypotheses, none of them satisfactory, were advanced to explain the loss of signal strength during the day, which came to be known as the "daylight effect." Marconi's reaction was characteristic; he began experimenting to extend the daylight range. His observations led him to try using longer waves; and after much experimenting, he satisfied himself that they gave him an improvement in daytime reception; and he also found it easier with the longer waves to generate high power. The more he experimented and observed, the more he was led in the direction of longer wave lengths. Other investigators in several countries arrived at the same conclusion, and without further thought, transoceanic communication went down the road of longer and longer wave lengths. Two decades later, the world was to be shown by Marconi that the road to world-wide communication lay in the opposite direction—the direction of short waves.

The goal of the pioneers was transoceanic communication, competitive financially with the solidly established cable systems. Toward that end the best technical brains of the art were directed, in the development of transmitters of higher and higher power and in the search for more sensitive detectors and more efficient antennas.

During the five or six years following the reception of transatlantic signals at St. Johns, Newfoundland, Marconi carried on ceaseless experiments, of which he has left an all too incomplete account. They culminated in the establishment during 1907 of the first transoceanic radio service, between stations at Glace Bay, Nova Scotia, and Clifden, Ireland. Spark transmitters of about 50 kilowatts power operating on wave lengths of several thousand meters were employed, with receivers using simple rectifying detectors, whose response depended entirely on the energy that could be abstracted from the incoming wave. Such a device as a vacuum tube amplifier was then a thing undreamed of. Continuity of service could be described as "somewhat uncertain."

Five more years of experience with the vagaries of the North Atlantic transmission path brought about a gradual lengthening of the waves of the two stations to approximately 5,000 and 6,000 meters respectively, with some improvement in the daytime service. During these dark ages of transoceanic communication, laborious development work was carried on by a number of organizations to produce a substitute for the imperfect spark system of transmission; and by 1913 several continuous wave generators, giving greater power than the spark system, were in operation. All efforts, as before, were centered on producing

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waves that were miles in length. The idea of shortening the waves for long distance service, instead of lengthening them, never occurred to anyone.

During this age of darkness, there was yet another instance of a light hidden under a bushel. In 1906 the 3-electrode vacuum tube—or "audion," as it was named—had been invented by Dr. Lee DeForest and put to use as a detector. Today the 3-electrode tube, in its manifold uses, is the key element in all radio transmission and reception. Yet for 6 years after it was invented it was merely another device, somewhat more sensitive than the crystals of the time, for changing radio impulses into currents within the audible range. It had no other use or purpose.

It has been a matter of wonderment that the audion, with its almost miraculous potentialities, was neglected by the art for 6 years, its mysteries unexplored. But in the perspective of today the reason is entirely clear. There was a theory of how it operated, which the art of the time generally accepted. Had the theory been right, the audion would have been a detector and nothing more. But the theory was wrong; and it remained for practical experimenters, in the face of what passed for knowledge at the time, to unravel the mysteries of the audion, disprove the theory and reveal the potentialities of what today is the primary tool of radio.

That was done in both the United States and Europe in 1912-13. The amplification of radio currents and the regenerative and oscillating circuits were discovered; and the sensitivity of radio receivers was increased a thousand-fold.

It would be pleasant to be able to record that communication improved in proportion, but that was not to be. The new method of reception made it possible for signals previously inaudible to be received as loudly as desired and it gave an improvement in radio communication, during certain parts of the day, that was beyond the wildest hopes of the inventors. But it also brought into focus a new problem, only less serious than the one that had been solved—the problem of atmospheric disturbances, or "static." So feeble were the signals that could be brought up to audible strength, and so great were the distances over which communication could now be carried on in the absence of static, that when static was present even on levels that previously would have passed unnoticed—it became the major factor limiting communication. It appeared, therefore, that still higher transmitter power would have to be generated to override the static, and that still longer wave lengths, with more expensive transmitter equipment, would have to be employed.

By the end of World War I, the radio communication companies had put a major part of their resources into the development of longwave, high-power transmitters of a variety of types—spark, quenched spark, timed spark, arc, the high frequency alternators of various countries (Alexanderson in the United States, Von Arco and Goldschmidt in Germany, and Latour in France) and the long wave vacuum tube generator. Waves 10,000 meters long were the order of the day. To radiate such waves, costly antenna structures had been erected, some almost 1,000 feet high and a mile long. Transoceanic communication had developed into a financial operation of frightening proportions.

It was an exasperating situation. The improved receiving means made it possible to operate perfectly, with relatively low power, during the undisturbed periods of the early morning hours. But with the coming of atmospheric disturbances in the afternoon and evening from electrical storms originating in the tropics, reception from even the highest powered transmitters was frequently blotted out. During such periods our best brute force method of more and more power (powers had reached the 500 kilowatt point) failed to match up to the forces of nature.

While we damned nature for its perversity in creating the static, we were happy about our ingenious transmitting and receiving equipment, which worked so well in the absence of disturbances. The idea that there might be a way of working with the forces of nature, rather than against them, seems to have been beyond the imagination of those working in the art. Another basic discovery was required to get off the dead-end road. Marconi was destined to make that discovery, but only after the chance to make it was repeatedly missed—by him and others—for nearly three years.

The ending of World War I released the experimental energies of a very able engineer of the British Marconi

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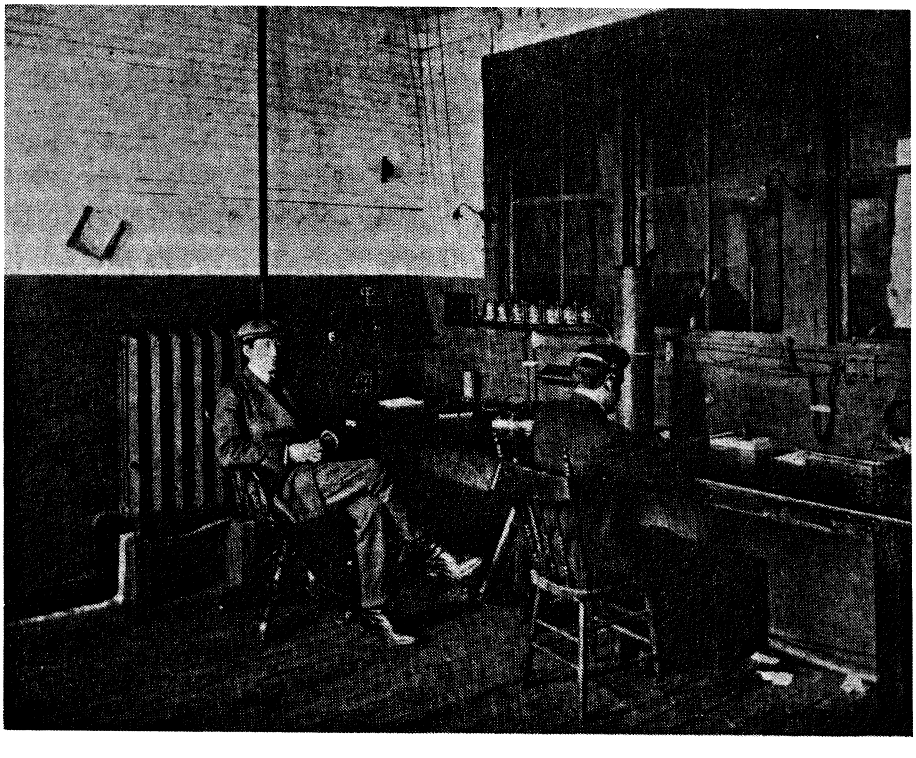
Marconi and operator at Glace Bay receiving station.



Wrong Roads and Missed Chances—Some Ancient Radio History

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Company, C. S. Franklin. Following up some work of Marconi for the Italian Army with short wave directive beams, Franklin established a telephone circuit between London (Hendon) and Birmingham in 1920, on the extremely short wave of 15 meters. That wave length was chosen—not for any expected advantage in transmission—but because it was easy to set up a reflecting antenna for waves of that order, and because loss of range, i.e., the "daylight effect" does not occur over so short a transmission path (100 miles). The Hendon and Birmingham transmitters had effective radiated power of about 4 kilowatts, and the system worked well. The significance of the Hendon-Birmingham circuit in this chapter of radio history will appear presently.

The radio amateur comes into the story at this point. American and British amateurs had been talking for years about organizing a test to determine whether the wave lengths on which they were allowed to work—the commercially "useless" ones of 200 meters and under—could span the Atlantic—during the hours of darkness, of course. Such a test was finally organized in 1920, on the 200 meter wave length. It failed. In the next year, another test was organized. Though all prophesies were that it too would fail, in fact a score of United States amateur call letters were identified in the British Isles in December 1921, two of them from stations with power of less than 100 watts; and one of the stations, Station 1BCG in Greenwich, Connecticut, succeeded also in transmitting a complete message.

But the signals could be received only during the night hours of the Atlantic path; they ended with sunrise at its eastern end and did not reappear until after sunset at its western end. While the results caused a flurry of interest for a time, it soon died down, since a system that would work only at night was of no commercial importance. Though everyone was surprised that a 200 meter wave could span the Atlantic, neither the commercial companies nor those who took part in the tests were stimulated to investigate the shorter waves further. I took part in the construction of the 1BCG transmitter and also in the decision to dismantle it after the test, when the question of further investigation was discussed. Why investigate something with so fatal a defect—it could work only part of the time? Marconi seems to have been the only man whose imagination was fired by the spanning of the ocean by the stations of the amateurs.

In a paper presented before the American Institute of Electrical Engineers and the Institute of Radio Engineers in New York City in June 1922, Marconi told about some of his recent work in radio, including the work for the Italian Army with directive beams and the 15 meter Hendon to Birmingham telephone circuit. He suggested that radio has perhaps got into a rut by confining practically all its research to the long waves, and that more attention should be given to the shorter waves; and he summed up his remarks on the subject with these prophetic words: "I have brought these results and ideas to your notice as I feel —and perhaps you will agree with me— that the study of short electric waves, although sadly neglected practically all through the history of wireless, is still likely to develop in many unexpected directions, and open up new fields of profitable research."

Upon his return to England, Marconi began a series of classic experiments from the historic Poldhu site, which took him on a cruise in his yacht "Elettra" to the Cape Verde Islands in the South Atlantic during the spring of 1923. He had set up a transmitter at Poldhu on the longest "short" wave for which it was then practicable to build a reflecting beam antenna—97 meters. He listened to the Poldhu signals as he cruised south, and found them to be extraordinarily good. In the Cape Verde Islands, over 2,500 miles from the transmitter they were far better than any signals that had ever been received over a comparable distance from a high power long wave station. Marconi reported that even when the power at Poldhu had been reduced to one kilowatt, its signals at night were still better than those received from the highest powered transoceanic stations in the British Isles. While the usual disappearance of the signals during daylight hours occurred, Marconi observed that the signals lasted for a time after sunrise at Poldhu and that they became audible again before darkness had set in at the Cape Verde Islands.

That observation led him to suspect that some new phenomenon was present in the short wave band; and after his return to England he laid out a program of further experimentation for the following year, when he would compare the signals at 90 meters with those on a number of shorter wave lengths, down to the region of 30 meters. In 1924, he cruised through the Mediterranean to the coast of Syria; and in Beyrouth harbor in September of that year he made the astounding observation that the signals on the 32 meter wave from Poldhu, some 2,400 miles away, held in throughout the day—they were in fact as good as the night time signals, whereas a longer wave of 92 meters, on the same power, behaved as at the Cape Verde Islands. What Marconi was observing was transmission by reflection from that ionized layer of the upper atmosphere which later became known as the F_2 layer, after years of observations had laid bare the mechanism by which the effect was produced. But as with Marconi's first discovery, his practical achievement was years ahead of the theory.

Returning to England within a month's time, Marconi sent notification of scheduled transmissions on 32 meters to Argentina, Australia, Brazil, Canada and the United States; and at the appointed times the daylight signals were received in all those countries. From the end of the earth—far-off Australia—came a report of successful reception for 23½ hours out of the 24.

These astonishing results became still more astonishing when it is remembered that Marconi was using only a few percent of the power of the transoceanic long-wave stations, and was unable to take advantage of his directive beam antenna because of the diversity of the paths of transmission to the various receiving points.

As sometimes happens with radically new discoveries, the significance of Marconi's results was not generally appreciated, at first, outside his own organization. As in the case of his original discovery, what he had done was too far out of line with established teachings to be accepted in advance of a physical demonstration of the result. But while

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others hesitated, Marconi, supported by the brilliant engineering of Franklin, moved rapidly, and by the end of 1927 short wave beam transmitters were operating between England and all the principal parts of the Empire—and at speeds (100 words per minute) that no long wave transmitter or cable had ever approached. The long waves were obsolete and the cables had become a secondary means of communication.

Today, all but a few percent of the world's long distance radio communication is carried out on wave-lengths less than ¼ the length of the waves originally allotted the amateurs in the 200 meters that no one else wanted. Perhaps the best measure of the advance from the era of the "grounded" wave is that it is now routine for amateurs the world over, with a few hundred dollars worth of equipment, to communicate with each other, and the "working" of several continents in a single day is no longer the subject of comment.

We can return now to one of the great missed chances—the chance that every American amateur and radio experimenter had had to tune in the Hendon-Birmingham beam telephone as early as 1922 and discover the daylight wave before Marconi. The Great Circle course of the Hendon beam lay across Eastern Canada and the United States. The 15 meter wave, as was later found, was a better daylight wave than those in the 30 meter range, though it was not effective at night. Full information about the Hendon station was available from Franklin's and Marconi's publications, and all necessary information about the most effective means of receiving such waves—the superheterodyne—had been published.

Had any radio experimenter in the United States thought to set up a superheterodyne for 15 meters and listen for the Hendon signals during the daytime, he would almost inevitable have heard them at some time during the day and he, instead of Marconi, would have discovered the daylight wave. But no one had the imagination to set up a receiver and listen. We all "knew" too much about propagation; only a madman in those days would have proposed to receive 15 meter signals across the North Atlantic, especially during daylight hours.

There is, however, a consolation for the American experimenters who missed the chance. The master experimenter himself, Marconi, also missed it. Though for more than 20 years he had made it a practice on voyages to the United States to take along receivers to listen to his British stations, when he crossed the Atlantic in the "Elettra" in 1922 it seems not to have occurred to him to take along a 15 meter receiver and listen to Hendon. Had he done so, and turned the Hendon beam to follow the yacht, he would have discovered the daylight wave two years before he actually did.

In retrospect, no one can regret that it was Marconi who made the great discovery. A reading of his account of his cruises shows that this was no chance discovery, but the result of a careful search by the one man who was able to define the limits of his own knowledge. Marconi set out on a thorough and painstaking exploration of what lay beyond those limits, and his search was rewarded by the success it deserved. To Marconi and those who worked with him goes the credit for the great discovery that put radio in first place in the field of world communication.

It is seldom given to a man to make two great discoveries, as Marconi did. He created the practical art of radio communication; and a generation later, when the limits of its ability to conquer distance seemed to have been reached, he came along with the discovery that made world-wide radio communication a reality.

The lesson of his work is clear-cut. He did not unlock the secrets of radio by exercise of some superior reasoning process. He studied the phenomena of radio as he encountered them, with an inquiring and open mind; as he let Nature and his apparatus get the answers for him. The key to his achievement is that he was able to appreciate the limits of his own knowledge, and to doubt what others were ready to accept as dogma. For that rare ability and his infinite perseverance he gained the reward that always awaits the true discoverer—he builded better than he knew.

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Editor HUGH S. POCOCK, M.I.E.E. Technical Editor Prof. G. W. O. HOWE, D.Sc., M.I.E.E.

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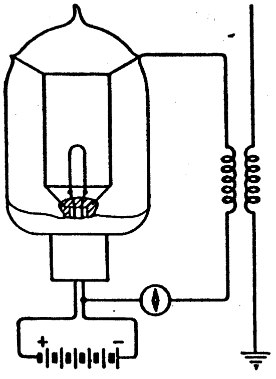
Early Radio Inventions

AT a special session of the American Institute of Electrical Engineers on January 27th, the 1942 Edison Medal, the highest award of the Institute, was presented to Edwin H. Armstrong, professor of electrical engineering at Columbia University, New York. The presentation address was made by Professor Alan Hazeltine; this address and Professor Armstrong's reply are published in the April number of *Electrical Engineering*. No one with a knowledge of the history of the development of radio science would question for a moment the outstanding achievements of Armstrong which amply qualify him for the distinction thus conferred upon him. In making the presentation address on such an occasion the speaker would naturally concentrate on the achievements of the recipient, but the following extract from the address surely shows a lack of generosity to those workers who filled in the gap between Edison and Armstrong.

"If we review," says Hazeltine, "the advances in electrical technology in the past 25 years, one development stands out from all others, electronics, and specifically the application of the three-electrode vacuum tube. It is appropriate to recall here that the original electronic tube was the two-electrode tube of Edison, in whose honour the Edison Medal was established. Others subsequently applied this "Edison effect" in radio detection and introduced the control electrode, but the action was viewed as that of a trigger, as in the modern thyratron, which is of limited application. The real foundation for the unlimited development which we have witnessed was laid by Doctor Edwin Howard Armstrong in an article published in the *Electrical World* in December, 1914. Here the common engineering tool, the characteristic curve, was employed for the first time to show how the tube amplifies, and the theory was substantiated by oscillograms which Armstrong had taken. The previously mysterious action of the tube as a rectifying detector with a grid capacitor was elucidated in the same way. . . . I also remember the excitement produced a few months later by Armstrong's first paper before the Institute of Radio Engineers on his feed-back circuit, which employed this theory to give undreamed-of amplification of weak radio signals and permitted the general use of heterodyne reception by providing for the first time a source of continuous oscillations of frequencies as high as any then used for radio transmision." The way in which Prof. Hazeltine skates lightly over the work of others previous to Armstrong is probably explained when he says: "These publications of Armstrong started my own work in radio, and profoundly affected my subsequent career, as they have affected the careers of many others. It is rather hard now to take ourselves back to conditions in radio prior to Armstrong." This is undoubtedly so in the case of the vast majority of those now interested in radio; they will find it difficult to imagine a world in which a three-electrode valve was unknown, and equally difficult to say who laid "the real foundation for the unlimited development which we have witnessed," an achievement the credit for which is given by Hazeltine to Armstrong.

Edison discovered—to quote his own words

—"that if a conducting substance is interposed anywhere in the vacuous space within the globe of an incandescent electric lamp, and said conducting substance is connected outside of the lamp with one terminal, preferably the positive one, of the incandescent conductor, a portion of the current will, when the lamp is in operation, pass through the shunt circuit thus formed, which shunt includes a portion of the vacuous space within the lamp. The current I have found to be proportional to the degree of incandescence of the conductor, or candle-power, of the lamp." Except for the words "preferably the positive one" there is no reference in this 1883 patent to the unidirectional property of the lamp; it was merely a device to connect across the d.c. mains and give a small shunt current which varied considerably when the voltage of the mains varied, and it thus provided a sensitive indicator of the mains voltage. During the following twenty-one years several physicists, notably Elster and Geitel, and also Fleming, investigated the properties of the Edison device, but it was not until 1904 that anyone suggested making use of its unidirectional property; in that year Fleming had the brain-wave to use it as a rectifier of alternating currents and specially as a detector of radio signals. Although he claimed to have discovered the unilateral conductivity, and subsequently had to amend the specification by disclaimer, and although there is no suggestion of an anode battery, and Fleming admitted that the device was not so sensitive as a coherer or magnetic detector, this patent of Fleming is undoubtedly one of the great landmarks of radio history; it was the first suggestion that thermionics could be applied to radio.

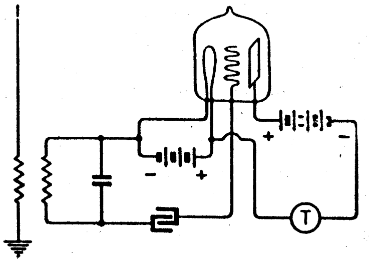


Fleming, 1905

de Forest's Great Invention

In 1906 de Forest read a paper before the American Institute of Electrical Engineers in which he described the use of a diode with a battery in the anode-filament circuit, and said: "When an independent external source of electromotive force is applied in the manner I have described, the action becomes quite different. It then operates as a relay to the Hertzian energy instead of merely rectifying this energy."

This paper of de Forest's also contains the germs of other improvements in the construction and use of thermionic valves. He refers to the superiority of tantalum and other of the new filament materials over carbon, and states that, although he had not been able to use the tungsten filament, he thought that it might give even better results. Further, he showed that it was not necessary to connect the oscillatory circuit to the anode, but that it might be connected to a separate electrode, a third electrode, surrounding the glass vessel, so arranged that its variation of potential controlled the current passing through the valve.



de Forest, 1906

Probably the greatest single invention in the whole history of the subject was made by Lee de Forest in 1906, when he inserted the third electrode in the form of a grid between the cathode and anode. To appreciate the importance of de Forest's contribution one has only to compare the two diagrams reproduced here from the patent specifications of Fleming and de Forest. Except for the absence of a grid-leak, de Forest's diagram might almost be dated 1943. The third claim of the patent specification is for "an oscillation detector comprising an evacuated vessel, two electrodes enclosed within such vessel, means for heating one of said electrodes, and a grid-shaped member of conducting material enclosed within said vessel and interposed between said electrodes." This will surely rank for all time as one of the greatest inventions of radio telegraphy.

It will be noticed that this invention relates to an oscillation detector and not to an amplifier, but ten weeks before this de Forest had applied for a patent for a three-electrode amplifier, the fourth claim of which reads as follows: "In a device for amplifying electrical currents, an evacuated vessel, three electrodes sealed within such vessel, means for heating one of said electrodes, a local receiving-current including two of said electrodes, and means for passing the current to be amplified between one of the electrodes which is included in the receiving circuit and the third electrode." The sixth claim is somewhat more precise: "In a device for amplifying electric currents, an evacuated vessel, a heated electrode and two non-heated electrodes sealed within said vessel, the non-heated electrodes being unequally spaced with respect to said heated electrode, a local receiving circuit including said heated electrode and that one of the non-heated electrodes which has the greater separation from the heated electrode, and means for passing the current to be amplified between the heated electrode and the other non-heated electrode."

Within the space of a few months de Forest had thus invented the triode amplifier and the triode detector, and, starting from the idea of a diode with a band of metal foil around the waist of the bulb to act as a control electrode, had put the third electrode inside the bulb and then given it the form of a grid interposed between the anode and cathode. All this happened within the latter half of the year 1906. Although we doubt whether it is true, as Dr. Hazeltine suggests, that the action was viewed as that of a trigger, there is no doubt that de Forest had some very strange ideas as to what was happening in the bulb. The following extract from his amplifier patent is almost incredible. "The current to be amplified may be impressed upon the medium intervening between the electrodes *D′* and *E*, and thereby alter, by electrostatic attraction, the separation between the electrodes. In this case *D′* may be a strip of platinum-foil, and the slightest approach thereof toward the filament will act to slightly cool the gaseous medium, and thereby alter the current in the local circuit, or, if *D′* is rigid, the increase in electrostatic attraction between *D′* and *E* will cause *E* [i.e., the filament] to recede from *D*, and thereby alter the current in the local circuit." In extenuation we would point out that this was written in 1906. It was eight years later in 1914 that Armstrong published his paper showing clearly with the aid of characteristic curves how de Forest's audion really functioned.

The Invention of the Valve Oscillator

In 1917 Armstrong was awarded the first Medal of Honour of the Institute of Radio Engineers for his work on regeneration and the generation of oscillations by means of thermionic valves, but the credit for this invention was the subject of a lengthy lawsuit between Armstrong and de Forest. The Commissioner of Patents awarded priority to Armstrong, but this was reversed on appeal and the Supreme Court decided in favour of de Forest. Armstrong then returned the Medal to the Institute in 1934, but they very properly declined to take it back and reaffirmed the award. It is noteworthy that the judgment of the Court of Appeals says: "Especially are we impressed by the party Armstrong and his witnesses. We have no doubt but what he produced the invention at the time alleged, and did all the things attributed to him by the testimony, as set forth in this record. His earliest claim to a conception of this invention is October, 1912, followed by a witnessed sketch on January 31st, 1913. . . . Coming, therefore, to de Forest's case, the Examiner of Interferences found that in the experiment of August 6th, 1912, the repeating circuit used as an amplifier of telephonic currents was modified by a connection between the plate-filament circuit and the grid-filament circuit. This resulted in the production of a beautiful clear tone. This, the witnesses have testified, was due to the audion generating oscillations or alternating current due to the feed-back action and was understood by them at the time of the experiment." This was the view taken by the Supreme Court, and so, in the invention of the valve oscillator, de Forest beat Armstrong by a few months.

In conclusion, we would quote from A. H. Morse's comment on this judgment in his "Radio: Beam and Broadcast," published in 1925. "Armstrong's work in radio is such that, had he no patented or patentable inventions—and he has many—he would still rank as one of the foremost exponents of the art."

G. W. O. H.

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May 1913	Theory of Tuned Circuits -- *Edwin H. Armstrong*
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Fall 1984	75th Anniversary Yearbook: Edwin H. Armstrong - An Independent Inventor in a Corporate Age -- *Dr. James E. Brittain*

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by **Lawrence Lessing**

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Some Recent Developments in Multiplex Transmission of Frequency Modulated Broadcast Signals. *Proceedings of The Radio Club of America,* October, 1953.

UNITED STATES PATENTS GRANTED TO EDWIN H. ARMSTRONG

NUMBER	DATE	SUBJECT
1,113,146	1914	Wireless receiving system.
1,334,165	1920	Electric-wave transmission. (Pupin & Armstrong)
1,336,378	1920	Antenna with distributed positive resistance. (Pupin & Armstrong)
1,342,885	1920	Receiving high-frequency oscillations.
1,388,441	1921	Multiple antenna for electrical wave transmission. (Pupin & Armstrong)
1,415,845	1922	Selectively opposing impedance to receive electrical oscillations. (Pupin & Armstrong)
1,416,061	1922	Radio-receiving system having high selectivity. (Pupin & Armstrong)
1,424,065	1922	Signaling system.
1,502,875	1924	Tone-producing radio receiver. (Pupin & Armstrong)
1,539,820	1925	Wave signaling system.
1,539,821	1925	Wave signaling system.
1,539,822	1925	Wave signaling system.
1,541,780	1925	Wave signaling system.
1,545,724	1925	Wave signaling system.
1,611,848	1926	Wireless receiving system for continuous waves.
1,675,323	1928	Wave signaling system.
1,716,573	1929	Wave signaling system.
1,941,066	1933	Radio signaling system.
1,941,067	1933	Radio broadcasting and receiving.
1,941,068	1933	Radio signaling.
1,941,069	1933	Radio signaling.
1,941,447	1933	Radiotelephone signaling.
2,024,138	1935	Radio signaling system.
2,063,074	1936	Radio transmitting system.
2,082,935	1937	Radio signaling system.
2,098,698	1937	Radio transmitting system.
2,104,011	1938	Radio signaling system.
2,104,012	1938	Multiplex radio signaling system.
2,116,501	1938	Radio receiving system.
2,116,502	1938	Radio receiving system.
2,122,401	1938	Frequency changing system.
2,130,172	1938	Radio transmitting system.
2,169,212	1939	Radio transmitting system.
2,203,712	1940	Radio transmitting system.
2,215,284	1940	Frequency modulation signaling system.

TWO RICH MINDS -- ONE POOR INVENTION

by **William E. Denk**, W3IGU **(M)**

Adapted from a Paper published in the *The Antique Radio Gazette,* Vol. 15, no. 1, March 1987

Even before the founding of the first association devoted to the preservation of the history and gear of early wireless, this writer had started his collection of patents having special significance in the early development of the communications technologies. Patents such as Edison's on the phonograph, Bell's patent on the telephone, the Morse patents on the telegraph, Marconi's earliest patents on his wireless transmitting and receiving systems, Fleming's patent on the vacuum tube diode detector, the early crystal detector patents of Bose, Dunwoody, and Pickard, the Hazeltine neutrodyne patent -- hundreds in all. This is a phase of our hobby that requires very little space, and it can be most interesting and revealing.

One of the early patents, after more careful study and in spite of the eminence of the named co-inventors, does not seem to fit into this collection of really significant patents. Had the inventors been a pair of unknowns, the patent surely would have been discarded or, at best, retained for its amusement value.

One of the inventors was Michael I. Pupin, Professor of Mathematics at Columbia University, and the inventor of the telephone repeater or Pupin coil which greatly improved long-distance land-line telephony. His patent covering that development was acquired by Bell Telephone Company in 1901. Other of his patents on tuning systems were licensed to the Marconi Company.

The other co-inventor was Edwin H. Armstrong who needs no introduction to radio historians. Armstrong studied under Professor Pupin while at Columbia University where Armstrong received his E.E. degree in 1913.

The patent here in question is U.S. Patent No. 1,336,378, *Antenna with Distributed Positive Resistance* application filed October 1, 1915 and issued April 6, 1920. The single page of drawing with its Fig. 1 and Fig. 2 is reproduced here.

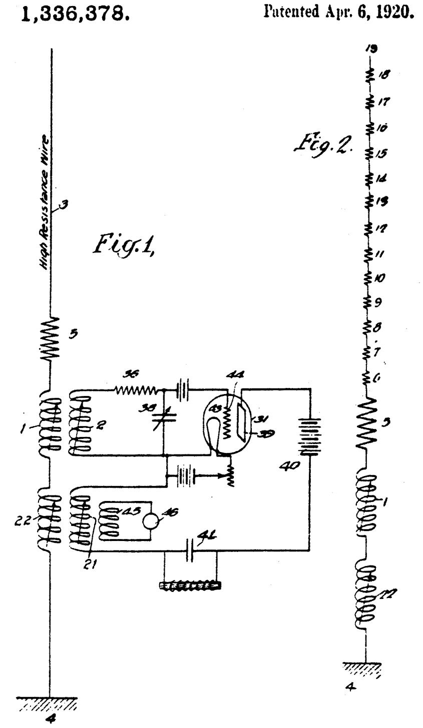
To adjust our thinking to the filing date, 1915, recall that deForest filed his patent application on the triode on January 29, 1907; Armstrong filed his application on the regenerative detector on October 29, 1913 and his application on the superheterodyne receiver on February 8, 1919.

William E. Denk

For an understanding of the objective of Messrs. Pupin and Armstrong which, broadly, was to reduce the effects of static on radio reception, the second paragraph of the patent specification is reproduced below in its entirety:

> The invention relates to receiving wave conductors which are loaded with resistance to screen them against the disturbing effects of electrical waves, and particularly those waves which have the character of electrical pulses of short duration, known in the art as

> "atmospherics" or "strays." A resistance introduced into the receiving conductor, called the receiving antenna in wireless transmissions, will diminish the effects of the disturbing waves and pulses, but it will also diminish to the same degree the effect of the waves which are to be received, *unless the introduced resistance is properly placed.* (emphasis added) This invention gives definite rules which enable one skilled in the art to distribute the induced resistance so that it will diminish the effect of disturbing waves more than of the waves which are to be received.



Referring to Fig. 1 of the drawing, there is an antenna 3 of high resistance wire (as much as 300,000 ohms). This is connected to ground, represented by 4, by way of primary inductors 1 and 22. A resistor 5 is included serially in the antenna primary circuit; it may equal about "a quarter of the total introduced resistance." Fig. 2 of the patent is included merely to show that instead of using high resistance in the antenna (quite a practical problem!), it would be easier to use a large number of lumped resistors, 6 through 18. The inventors note that such an antenna would "act like a perfectly uniform wire of the same total resistance, if the lumps are so spaced that there are several per wavelength of the waves" to be received. According to the inventors, the function of resistor 5 "is to dissipate the electromagnetic energy during its passage from the antenna to the receiving apparatus.

For the simplest embodiment of the invention, ignore the entire vacuum tube circuit and observe only that detector 46 is coupled to the antenna primary coil 22 by way of coupling coil 45. Ignore also the interposed coil 21 which is part of the vacuum tube circuit. In describing this arrangement, the inventors make the unsupported statement that "we find that in such an antenna the effective resistance for waves to be received is a fractional part of the total resistance whereas, for electrical pulses of short duration, the effective resistance is substantially equal to the total resistance of the antenna." Their "pulses of short duration" are, of course, atmospherics or static against which the inventors desired to discriminate.

Claim 1 of the patent is directed broadly to the antenna of the type described thus far. It reads:

> 1. A receiving conductor for wireless wave transmission having a resistance load sufficiently high to screen the system effectively against disturbing electromagnetic waves impressed upon the conductor, the said resistance load being distributed along the conductor with substantial uniformity with respect to the wavelengths developed upon the conductor by the received signals.

Now to the preferred embodiment of the invention -- and here it becomes more interesting though no more convincing. The inventors describe the heretofore ignored vacuum tube circuit as "a resistance compensator...employed for the purpose of compensating a large resistance introduced into an antenna." This compensator is, simply, a regenerative system that reintroduces energy, taken from the antenna and applied to the grid circuit, back into the antenna circuit via plate coil 21, in such phase as to introduce a negative resistance in the antenna. In the words of the inventors, "This produces in the antenna a negative resistance reaction capable of reducing the resistance (of the antenna) to any predetermined limit for waves of selected frequency." This latter suggests that the inventors believed that the high built-in antenna resistance would be greatly diminished for the desired signals while remaining very high for atmospherics, thus discriminating strongly against static interference.

Claim 2 of the patent is like claim 1, reproduced above, but adds the following:

> and a resistance compensator connected to the conductor and adapted to reduce its effective resistance to any predetermined limit for receiving signals.

The writer found no reference to this patent in Maclauren's fine book *Invention and Innovation in the Radio Industry*, MacMillan Co., 1949, and didn't really expect to, but the following significant statement appears on page 184: "One of the major problems which Armstrong had been eager to solve was the elimination of static. His first work with Pupin had been in this field and, for eight years (1914 - 1922), he had wrestled with the task without making significant progress." Maclauren adds that, in an interview, Armstrong stated, "My early failures here were a chastening experience and it was two years before I regained sufficient confidence to tackle this particular problem once more."

As we all know now, Armstrong's new approach to static reduction was use of the UHF spectrum, higher power, wide-band frequency modulation, and amplitude limiters or clippers at the receiver.

On balance, it seems fair to conclude that the Pupin & Armstrong patent does *not* belong in the discard pile. Instead it will be retained as an interesting but unproductive step in man's long effort to minimize the effects of atmospherics on radio reception. And as for us more ordinary toilers, it has to be reassuring to know that occasional failure need not preclude ultimate success.

William E. Denk graduated from the University of North Dakota with the degrees BSEE in 1932, and MSEE in 1933. In 1936 - 37, he did a year of graduate study at MIT, then joined the engineering department at Philco but, in the same year, was invited to transfer to their Patent Department as a Patent Engineer. He was admitted to practice before the U.S. Patent Office as an Agent in 1946. He remained in the Patent Department, through Philco's acquisition by Ford in 1961, until retirement in 1974. After retirement, he served as Patent Consultant to a Philadelphia patent law firm where he was involved in both patent soliciting and patent litigation.

He was first licensed as a radio Amateur as 9FPC in 1928 and as W3IGU in 1976. He is a member of the Antique Wireless Association (AWA), the Society of Wireless Pioneers (SOWP), the Quarter Century Wireless Association (QCWA), and is an officer of the Antique Radio Club of America, Inc. (ARCA).

ADDRESS AT THE SECOND MAJOR ARMSTRONG AWARDS BANQUET OF THE ARMSTRONG MEMORIAL RESEARCH FOUNDATION.

by **Frank A. Gunther**

Presented at The Engineers Club, New York, N.Y., December 16, 1965

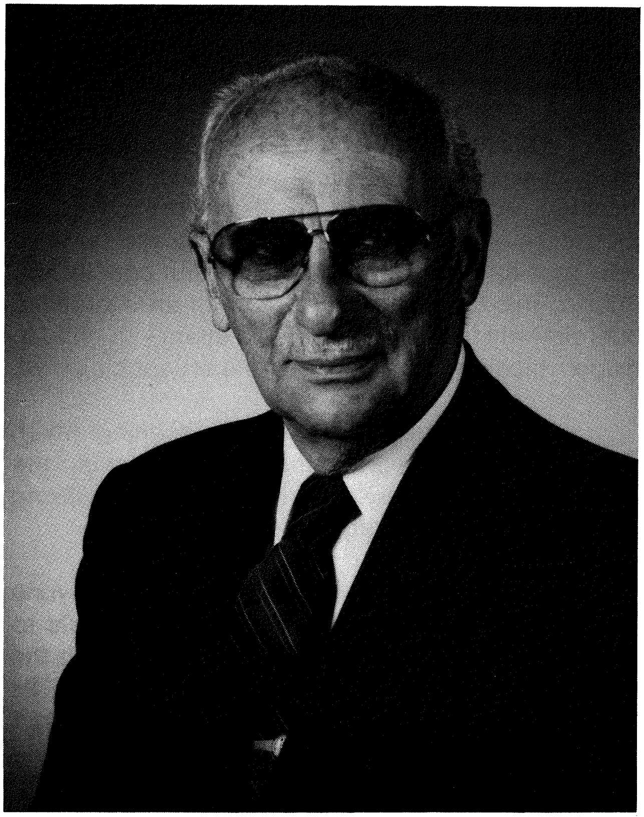
Editor's Note: The Armstrong Memorial Research Foundation was established to honor Armstrong's memory by perpetuating the principles that guided him in his life, and to aid in the continuation of the basic research carried on by him. In addition, the Foundation contributes by aiding the education and training of engineers and scientists doing basic applied research in electronics and related fields of science by making grants of money to educational institutions.

Mr. President, Mrs. Armstrong, Distinguished Guests, Ladies and Gentlemen:

We are assembled here tonight to pay honor to one of the most illustrious engineers and inventors in American history: Major Edwin Howard Armstrong. Simultaneously, we are honoring a number of those involved in one of the greatest inventions in radio history -- Frequency Modulation -- persons who have made use of this invention in a noteworthy manner to elevate to a higher plane the cultural, entertainment, and economic life of our citizens, as envisaged by the inventor. It is most regrettable that Major Armstrong did not survive to observe the full flowering of his brainchild which is now taking place.

It was with many qualms that I accepted the invitation of the Armstrong Memorial Research Foundation to be your speaker tonight. There are many here in the audience who have a much closer relationship to Major Armstrong and his work than I, and who should be much better qualified to deliver a eulogy to this great man.

I entered the FM picture during the initial stages of producing the equipment of the first experimental and commercial FM stations, and the field installations of that equipment. Yet, as a relatively late arrival on the scene of the Major's activities, I was most impressed with his clear and direct approach to all scientific problems, his complete dedication to his work, his faith in its ultimate success, and his warm personality. I shall always cherish my association with him.



Frank A. Gunther

It is not for me to expound on the Major's outstanding personal character and integrity. This already has been done by an excellent writer, Lawrence Lessing, in his book *Man of High Fidelity*, as well as in various articles by others, and in the Major's own lucid and straightforward technical papers and addresses.

I could not improve on these nor would attempt to repeat or rehash the facts stated in those documents. Rather, tonight, I should prefer to emphasize in this tribute some of the effects of Major Armstrong's inventions on the radio industry and the entire spectrum of communications.

Many here whose main interest lies in FM broadcasting may possibly have developed a myopic attitude on the vast breadth of applications of FM; that is, their comprehension of the impact of FM as well as other inventions of the Major may be restricted to a severely limited sector of the radio horizon -- that in which they are most interested: FM broadcasting. Let us remind ourselves that no tribute to Major Armstrong could be complete without a realization of the worldwide importance of all of his work. In fact, had it not been for the regenerative circuit, neither FM nor any other type of radio communication would ever have become so essential a tool in the hand of mankind.

Possibly it can be said that eventually this basic principle of the radio art would have been invented regardless of the work of Armstrong, but the fact remains that he first perceived and pursued this giant forward step to a successful conclusion. Prior to this time, radio was more of an interesting but relatively ineffective scientific infant -- a child in diapers inching forward with an imperceptible crawl.

Regardless of false legal reasoning which disregarded or perverted the technical facts, the world scientific society is convinced that Armstrong is the true inventor of regeneration.

Returning to FM broadcasting, everyone knows about the efforts of entrenched interests to shelve or degrade the use of FM, together with the intervention of World War II which delayed its development. Now, with some encouragement from government sources, FM broadcasting including commercial and educational, boasts of some 1700 stations in the United States alone.

To listen to these stations, we have an estimated 30,000,000 or more receivers equipped with FM. To these figures, add the immense number of FM broadcasting stations and FM receivers in foreign lands where, particularly in Europe, the advantages of FM were recognized before they were in the United States and where, after World War II, the relative development of FM broadcasting far outstripped that in our country. Figures for FM operations overseas are incomplete but the world totals must be most impressive.

Dry statistics have no place in a talk of this nature, but it is interesting to compare what has been done with FM in other areas of our economy and national life. The Safety and Special Services include the following general categories of radio services using FM:

Broadcast studio links and remote pickups
Business and special applications
Emergency automobile service
Fire fighting
Forest products and forestry conservation
Highway maintenance
Industrial relocation
Manufacturing
Motor carriers
Petroleum production and distribution
Police and other local government services
Power generation and distribution
Press relay services
Railroads
Special emergency and State Guard units
Taxicab dispatching
Telephone maintenance

This array of services now has 350,000 FM transmitters in operation plus at least an equal number of FM receivers; truly a remarkable growth over the years.

We also should remember that the audio channels of TV transmissions utilize FM and there are approximately 70 million TV receivers in the United States alone. When all of these are added to the regular FM broadcast receiving equipment plus the FM equipment employed in Safety and Special Radio Services, the total use of FM in the U.S. is staggering. To this base, it should be noted that the National Aeronautical and Space Administration now is involved in the possibility of broadcasting radio signals directly from satellites into home receivers using FM. Tentative planning calls for one or more of these satellites to be in operation in the late 1960's or early 1970's. These satellite relays would broadcast directly to home or automobile radios with directional antennas. The effect of these satellites on our current FM broadcasting practices should be studied carefully.

One important use of FM should not be overlooked although the quantities in this case may appear somewhat insignificant. During World War II and thereafter, the Armed Forces of the United States found that FM could be put to use very effectively for a number of types of important circuits. The Armed Forces were not constrained in the utilization of FM by political and economic dictates which controlled its early civilian use. Consequently, great strides in the development of military FM communication became possible, and the Services themselves pioneered a number of developments. Depending upon deployment of forces, available commercial facilities, and assigned missions, FM is now used or under development for:

Air-to-air communications
Air-to-ground communications circuits
Mobile tactical field operations
Point-to-point tropospheric scatter systems
Point-To-Point microwave circuits
Satellite communications
Ship-to-shore circuits for amphibious operations
Ship-to-shore strategic tropospheric-scatter circuits
Space communications
Transportable tactical tropospheric-scatter terminals
Underwater radio communication circuits

The best estimates obtainable indicate that there currently are about 150,000 sets of FM equipment in use by the Armed Forces with much of it being of the multichannel variety. From personal knowledge, I can say that it is in use wherever our forces are deployed including Viet Nam and the Dominican Republic. The use of this equipment has become vital to the success of our military operations on a worldwide basis.

At this point, I want to give credit to the pioneers among FM broadcasters because these people -- with their faith and belief in FM, through solid financial support, hard work, promotion, and strong engineering development efforts -- gave the necessary impetus to the development of FM.These early efforts helped to demonstrate the complete practicability and usefulness of this mode of communications. These FM broadcast pioneers accelerated the adoption and use of FM by other services at a much earlier date than otherwise could be expected.

When we visualize the tremendous use of FM in radio and TV broadcasting, Safety and Special Radio Services and the military, we gain some idea of the impact of this invention upon the entire world. This alone should be a perpetual memorial to Major Armstrong, and an indestructible legacy from him to all peoples of the Earth.

However, we should deal with the Major's accomplishments in proper perspective and not restrict our consideration solely in the parochial vein of FM broadcasting. I repeat -- without the regenerative circuit devised by him, radio might have remained an interesting speculation just as it was in 1912. This same circuit became the general basis for the superheterodyne circuit which has become the foundation of practically all radio receivers regardless of the type of modulation employed. At about the same time that he invented the superheterodyne circuit, Armstrong also devised the super-regenerative circuit which enjoyed wide usage in radio receivers for a relatively short time. It was another important step in the development of radio despite its lack of sensitivity or ability to discriminate between two adjacent channels. The super-regenerative principle may still prove to be a most useful basis for future developments in radio, and that it should not be written off the books as an obsolescent development.

With regard to the super-regenerative circuit, within the past two days, an item in the press under a Washington dateline stated that a U.S. electronics firm had been in litigation with a foreign firm, with the U.S. firm claiming the other was infringing on a patent for a high-gain super-regenerative detector. Although the petition was denied, it would appear that the super-regenerative principle may have been re-invented and is in use again.

When all his inventions, developments, and other contributions to the radio art are viewed in relation to the benefits accruing to mankind and not solely with respect to FM broadcasting, I think that you'll agree that Major Armstrong's work has done more to advance the science of wireless communications than any since Marconi harnessed electromagnetic waves and initiated the true era of radio communications.

While those of us close to the industry may be very conscious of the value and importance of the Major's work, the general public only vaguely recognizes that he invented FM broadcasting and has little knowledge of the broad contributions he made to all types of radio communication and how dependent the development of the those rests upon his solid accomplishments.

My words, tonight, have attempted somewhat indirectly perhaps to support the objectives of the Armstrong Memorial Research Foundation. This organization was not founded solely to advance the art of FM broadcasting, important as this segment may be. The Foundation includes in its aims the support of continued basic research in which the Major was involved at Columbia University; assistance in the education and training of those engineers capable of performing basic applied research in electronics and associated scientific fields; granting of funds to educational institutions for research in the same fields; and provide scholarships and fellowships to deserving students in various scientific fields. These are highly laudable objectives and I know the Foundation is doing its best to carry them out. We should note the objectives are quite general and encompass the entire field of electronics.

Lastly, but of no less importance, is the objective of our Foundation to honor Major Armstrong by perpetuating the exemplary principles he exhibited so clearly and with so much integrity in his way of life and his methods of working. At this gathering tonight, we are striving to carry out this objective and pay him the honor which is his due. I am sure that we all unite at this moment in paying the highest tribute to our friend, foremost genius of radio in our generation, a sincere patriot and man of lofty character -- Major Edwin Howard Armstrong.

Mr. Frank A. Gunther, W2ALS, was the President of Radio Engineering Laboratories (REL) Division of Dynamics Corporation of America , and Executive Vice President of DCA, the parent company. He had forty years of continuous service with REL, and remains a member of the Board of Directors of DCA. He and a number of the REL staff were intimately associated with the early experimentation and development of frequency modulation in radio communication; the development of FM was led by Major E. H. Armstrong, its inventor. Mr. Gunther is a Director of the Armstrong Memorial Research Foundation and is a Past National President of the Armed Forces Communications and Electronics Association (AFCEA), a Life Fellow, Past President and currently a Director Emeritus of The Radio Club of America, and a Life Fellow of the IEEE. He also has served as a member of the National Industry Advisory Board of the FCC, serving on the Amateur Radio Services Section which is concerned with the regulation, coordination and operation of Amateur radio stations for public benefit during emergency periods.

A DISCUSSION OF L. P. LESSING'S UNUSUAL BIOGRAPHY "MAN OF HIGH FIDELITY: EDWIN HOWARD ARMSTRONG"

by **Capt. Pierre Boucheron, USN (ret.) (F)**

Originally published in *The Proceedings of The Radio Club of America*, Vol. 34, No. 1, March 1958

This is more than a book about a great American inventor, Howard Armstrong, and his basic contributions to the fast moving art of communications. It is also an accurate, though necessarily short, record of electrical signaling from Faraday's seminal discoveries in 1832 to Morse, Bell, Clerk-Maxwell, Lodge, Marconi and DeForest, and the great part played by the amateurs from 1900 on to the present day.

I first met Howard Armstrong at one of the early meetings of The Radio Club of America. Here was a band of dedicated boys, many still in knickerbockers, who called themselves "wireless experimenters," most of them equipped, as I was, with an one-inch spark coil, a varying length of untuned antenna, and a cat's whisker-crystal detector. My special benefactor at the time was George Eltz who later introduced me to Howard as well as to Ernest Amy, Tom Styles, Doctor Hudson, George Burghard, Randolph Runyon, Fred Klingenschmitt and Weddie Stokes who operated a more elaborate rig atop his father's New York hotel, the Ansonia.

In my scrapbook, I have a faded clipping dated November 30, 1910, that tells of a group of forty amateur wireless men, of which I was proudly one, who met in Astoria, L.I., to denounce the Depew Bill. Shortly after that, W.E.D. Stokes, Jr., the 14 year old president of The Radio Club went to Washington along with one of his father's attorneys to oppose this "dastardly Bill," a bill that was meant to kill off the amateur experimentations of those early days headed by our hero and star performer, Howard Armstrong.

I did not see much more of Howard until after we were all back in civilian life following World War I. Later, I saw much of him while I was editor of the original *Radio Amateur News*, and again many times in the outer office of another genius in the making, David Sarnoff, presided over by the lovely Esther Marion MacInnis, secretary to the then vice-president and general manager of the Radio Corporation of America, and to whom I reported as assistant for public relations. Howard, after his U.S. Army Signal Corps tour of duty as a major in France, had become an ardent Francophile and he liked to practice his A.E.F. French on me, a native of Paris.

Although Armstrong was a unique conceptor of original ideas, and therefore highly justified in defending to the utmost the children of his brain, there's an old saying among artists, authors and inventors that worthwhile ideas are often born in the minds of many men at exactly or nearly the same time. This truism is one that Armstrong refused to recognize. If he had been a little more tolerant, and I may add, more realistic and practical, he might have been a happier, less frustrated man during what should have been his "golden years."

One of the more telling chapters of this stark record of pure achievement, and one indicative of the kind of research that Lawrence Lessing displays throughout the book appears under Chapter XIII, *The Superheterodyne Feat.* I quote the first sentence because it is a prelude to an easy-to-understand outline, of the schematic circuit diagrams in this chapter:

> "The superheterodyne circuit was a brilliant display of Howard Armstrong's genius for taking up the seemingly unrelated facts and combining them, by intuitive thinking, logic and hard work, into new instruments of amazing effectiveness. The superheterodyne was not quite as basic an invention as the regenerative circuit, but it was a fundamentally new manipulation of electromagnetic waves so deft as to appear almost a feat of slight-of-hand. Even now, to the ordinary man, uncalloused by too much technical knowledge, it still appears as a magical box of tricks. To understand how it was accomplished and what it meant, it is necessary to go back a bit into some of the fundamentals of radio."

And Mr. Lessing does just that, so that any 14-year old pre-science, high school student will be more than fascinated not only by the superheterodyne feat but also by the other two pieces of electronic magic, the regenerative circuit and frequency modulation.

Of course, while Howard did the basic thinking, he had much valuable help from others. In the long list of friends and associates whom the colorful Armstrong drew around him over the years, there stand out three topflight men that come to mind at this time: the able research engineer, Harry W. Houck; the legally-trained George Burghard; and the general factotum, Thomas J. Styles. These three men, and others who came later, encouraged, assisted, advised, as well as helped in the technical development and legal handling of the three basic inventions -- not to forget helping Howard out of his usual preoccupation and social reticence. They insisted on occasional "let's get away from it all and have some fun" bits of relaxation. Later, there was romance, too, and 100 mph rides with Esther Marion in his Hispano-Suiza, the foreign sport car of the roaring 20's. He married the attractive secretary of the RCA executive suite on December 1, 1923. Esther, who had intelligence besides knowledge of stenography, proved to be a devoted and understanding helpmate for over thirty years.

The book, *Man of High Fidelity*, is a fast-moving word portrait of a brilliant inventor, eccentric yet withal quixotic genius -- a modern David who, however, was unable to subdue, let alone slay, the modern Goliath. Frustrated at the very end, he chose the only way out, as he saw it, with an exit and finality seldom found so tragic.

Let us not say too quickly that he should not have performed this final act of defeat. Here was a man of great personal honesty and intellectual capacity. As Judge Julius Mayer once said, Armstrong was a remarkably clear thinker at all times. Surely, Howard knew exactly what he was doing and why. There's an old proverb that says: "Those whom the gods would destroy, they first make mad." But this was not the act of a madman, of a deranged or neurotic mind, nor was it the act of a cornered "big shot" industrialist exposed by the higher-ups. This was disenchantment of the highest degree. Armstrong saw no way out without sacrificing principle and his high sense of justice. A more timid and mercenary soul would have compromised with the powerful corporation and the astute man at its helm.

Here then, is a beautifully done and sympathetic document about a strange and remarkable man. It is also an authentic report about a fast-disappearing species -- the contemporary sole inventor. Every attic and garage tinkerer, every young engineer starting out bravely on a career in electronics and mass communication -- indeed, every adult technician, communicator and commercial man of radio, television and the associated arts should read this fascinating biography of a great American. He or she will find not only inspiration of a sort, as well as usable information, but will understand better that nowadays the complexity of so-called free-enterprise, the "organized genius of modern corporations," and at times abuse of power, make it extremely difficult for any one brain to win singular acclaim -- and acceptance -- as an original inventor of a basically new electronic circuit, instrument, machine or device. With this better understanding, perhaps the embryonic inventor will pursue ways and means to protect himself by expert legal and patent law advice. Mr. Lessing makes this clearer when he says:

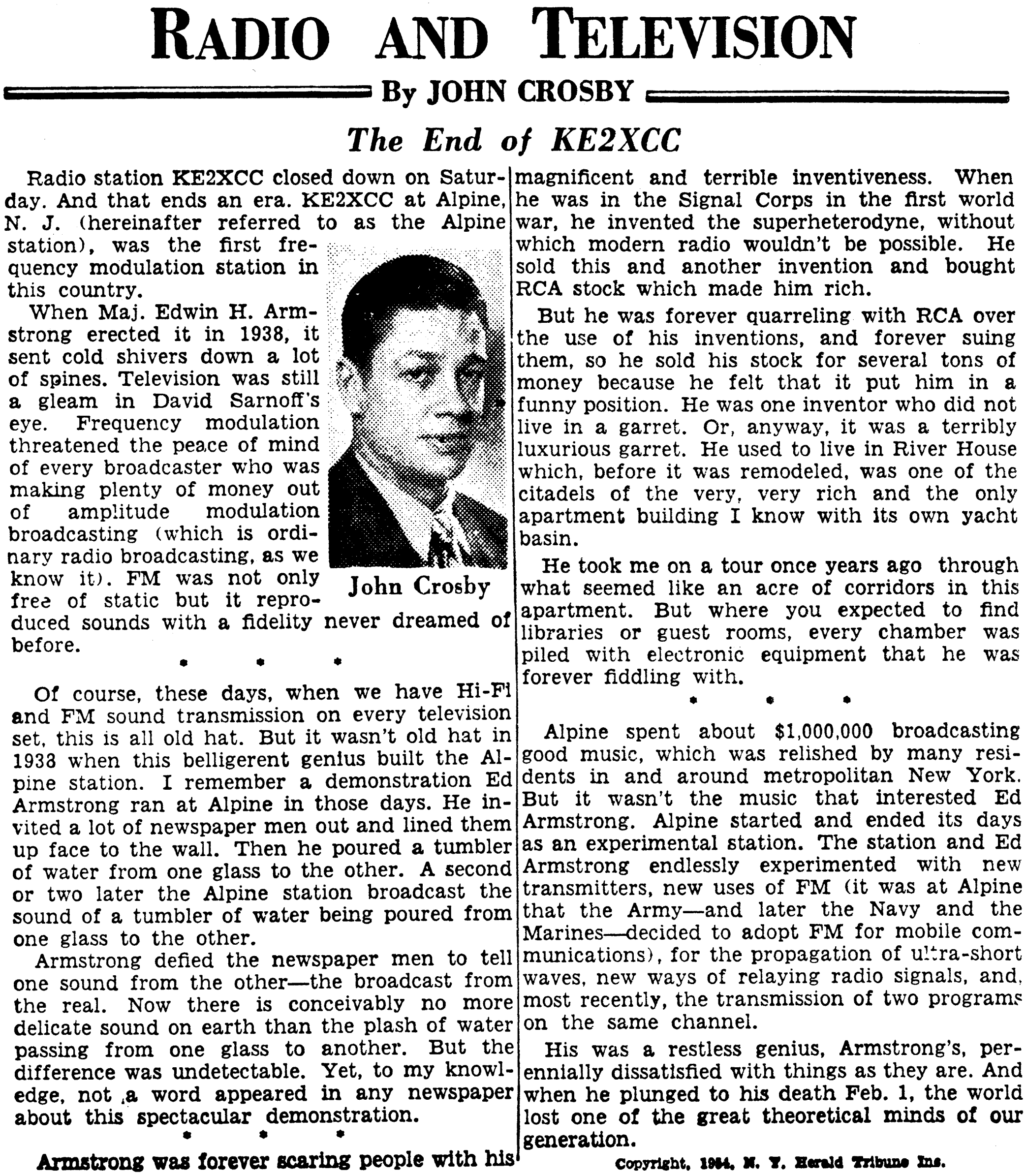
> "Until society devises some more rational means to affirm the title and rights of its scientific creators, inventors have no other avenue but patent law by which to defend their creations. U.S. patent law gives the inventor, in return for his full disclosure of a new device or process to society, a handsome embossed paper granting his exclusive possession, exploitation and assignment of his discovery for seventeen years. It gives him no more than this. It gives him no means to develop his invention or carry it into use. It grants him no defense of his rights except that which he can muster for himself in a court of law by his own energies and resources. By the time an invention gets into court it invariably involves large industrial forces battling for position, and the drama becomes turgid. Yet it still pivots on the inventor. In the case of great inventions, the human drama rises to an unholy pitch, for it turns upon the determination of the actual moment of creation."

This unusual biography should live a long time in patent circles and elsewhere because it not only exposes the machinations and sometimes utterly dishonest practices of corporations, as well as the stuffy, hide-bound mental processes of the Supreme Court justices, but this book also proves, step by step, logically and irrevocably that Howard Armstrong was the one and only inventor of the three basic circuit-systems. These three, the regenerative, the superheterodyne, and frequency modulation which last one gave us not only the "Hi-Fi" sound for television reproduction (a fact studiously never advertised by the powers-that-be), but the one invention that solved the baffling problem of static elimination. Indeed, "a new communication system of great beauty and utility was inaugurated -- that, and for good measure, a new kind of radar for the National Defense. Without these major accomplishments, radio and television as we know it today would have been well-nigh impossible.

In evaluating the originative work done by Howard Armstrong, we must not overlook or underestimate the invention of Lee De Forest of the triode tube or Audion. Certainly, the three element tube was a necessary contribution to the electronic art. For that matter, so was its antecedent, the Fleming two-element tube. It is a little far-fetched, however, to call any one contemporary inventor "The Father of Radio." If any one deserves that controversial title, it is Marconi.

Finally, and to return to Armstrong and De Forest, it is a pity that these two pioneers and antagonists could not have joined forces, patent-wise. What a team they would have made, and, properly advised by Messrs. McCormack, Houck and Burghard, and others in the De Forest camp, might have in great measure brought the powerful opposing corporations to less exhaustive, more equitable and rewarding terms.

Originally published in *The Proceedings of The Radio Club of America*, Vol. 34, no. 1, March 1958 as a book review of *Man of High Fidelity -- EDWIN HOWARD ARMSTRONG*, Lawrence Lessing, 1956. Published by J. B. Lippincott Co. 320 pages, 30 illustrations.



RADIO AND TELEVISION

By JOHN CROSBY

The End of KE2XCC

Radio station KE2XCC closed down on Saturday. And that ends an era. KE2XCC at Alpine, N. J. (hereinafter referred to as the Alpine station), was the first frequency modulation station in this country.

When Maj. Edwin H. Armstrong erected it in 1938, it sent cold shivers down a lot of spines. Television was still a gleam in David Sarnoff's eye. Frequency modulation threatened the peace of mind of every broadcaster who was making plenty of money out of amplitude modulation broadcasting (which is ordinary radio broadcasting, as we know it). FM was not only free of static but it reproduced sounds with a fidelity never dreamed of before.

John Crosby

* * *

Of course, these days, when we have Hi-Fi and FM sound transmission on every television set, this is all old hat. But it wasn't old hat in 1938 when this belligerent genius built the Alpine station. I remember a demonstration Ed Armstrong ran at Alpine in those days. He invited a lot of newspaper men out and lined them up face to the wall. Then he poured a tumbler of water from one glass to the other. A second or two later the Alpine station broadcast the sound of a tumbler of water being poured from one glass to the other.

Armstrong defied the newspaper men to tell one sound from the other—the broadcast from the real. Now there is conceivably no more delicate sound on earth than the plash of water passing from one glass to another. But the difference was undetectable. Yet, to my knowledge, not a word appeared in any newspaper about this spectacular demonstration.

* * *

Armstrong was forever scaring people with his magnificent and terrible inventiveness. When he was in the Signal Corps in the first world war, he invented the superheterodyne, without which modern radio wouldn't be possible. He sold this and another invention and bought RCA stock which made him rich.

But he was forever quarreling with RCA over the use of his inventions, and forever suing them, so he sold his stock for several tons of money because he felt that it put him in a funny position. He was one inventor who did not live in a garret. Or, anyway, it was a terribly luxurious garret. He used to live in River House which, before it was remodeled, was one of the citadels of the very, very rich and the only apartment building I know with its own yacht basin.

He took me on a tour once years ago through what seemed like an acre of corridors in this apartment. But where you expected to find libraries or guest rooms, every chamber was piled with electronic equipment that he was forever fiddling with.

* * *

Alpine spent about $1,000,000 broadcasting good music, which was relished by many residents in and around metropolitan New York. But it wasn't the music that interested Ed Armstrong. Alpine started and ended its days as an experimental station. The station and Ed Armstrong endlessly experimented with new transmitters, new uses of FM (it was at Alpine that the Army—and later the Navy and the Marines—decided to adopt FM for mobile communications), for the propagation of ultra-short waves, new ways of relaying radio signals, and, most recently, the transmission of two programs on the same channel.

His was a restless genius, Armstrong's, perennially dissatisfied with things as they are. And when he plunged to his death Feb. 1, the world lost one of the great theoretical minds of our generation.

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New York Herald Tribune.

HOW DID EDWIN HOWARD ARMSTRONG DIE ?

by **Francis H. Shepard, Jr., (LF and Director Emeritus)**

These reminiscences are the recollections of happenings of some 36 years ago and, therefore, may or may not be fully accurate; however, they are the sincere beliefs of the author, Frank Shepard.

Tradition has it that Edwin Howard Armstrong died from a fall from a window of his 13th story apartment in The River House in New York City, during the night of January 31 - February 1, 1954. He was found fully-clothed, wearing his overcoat, hat, gloves, and scarf at about 10 AM on the morning of February 1, on a roof overhanging the entryway of the building. There were no known witnesses to the fall but there were police statements that notes were found in the apartment implying that Armstrong took his own life.

Perhaps we should consider a few of the events that preceded his death.

Prior to my tenure as President of The Radio Club of America covering the period of 1954 - 1956, Edwin Howard Armstrong was obsessed with the activities of the McCarthy Senate Hearings regarding security breaks by low-echelon technicians in U.S. government laboratories. Armstrong tried desperately to get McCarthy to go after the higher-ups who authorized plane loads of secret information to leave the United States weekly via the Pacific, Siberia, and ultimately to Moscow. Armstrong was most outspoken on this subject but always was sidetracked to a Mr. Roy M. Cohn, Chief Counsel and assistant. A week or so before his death, Armstrong spoke to me about how Cohn was giving him (Armstrong) the run-around and was keeping him from talking with Senator McCarthy.

During several of the suppers which preceded the meetings of The Radio Club, the late S. Young White (of Loftin-White fame) who claimed to have worked for the U.S. Department of State and to have knowledge of Communist activities in our governments and in our hospitals, told Armstrong, "You'd better shut up or you won't be around for long."

White told the story of Snellenburg who was responsible for reviewing U.S. patent applications to decide whether they should be classified as secret, or not. He was found dead, accused of the murder of his wife and (I think) children by shooting. He was found dead with two bullets in his head.

White said: "Major, don't go into a New York hospital or you'll come out with ten percent mentality."

Armstrong publicly disregarded these warnings; however, I feel that they did affect him. On Sunday mornings, he would phone my home and talk for a couple of hours in obviously guarded tones. I commented to my wife, at the time, that Armstrong acted like he felt that his phone line was tapped.

I do not have a shred of proof that Armstrong did not commit suicide. However, association with him as a friend and admirer made me know that setbacks were, to him, a challenge. He was a fighter,not a quitter.

The purported notes could have been forged. He could have been drugged or somehow coerced into making statements. Wishy-washy words were not his cup of tea. His mode of dress suggests that he had met someone earlier in the evening or planned to meet someone. Was he duped into opening the window on that wintry night? And could he have been pushed?

I want to remember Armstrong as a strong, vibrant, creative fighter -- not a quitter.

Armstrong, FM Inventor, Dies In Leap From East Side Suite

Pioneer in Radio, 63, Plunges From River House Window —Left a Note for Wife

Maj. Edwin H. Armstrong, whose inventions provided much of the basis for modern broadcasting, was found dead yesterday morning on a third-floor balcony of River House, 435 East Fifty-second Street. The 63-year-old electrical engineer had plunged from a window of his luxurious thirteenth-floor apartment, apparently late Sunday evening or during the night.

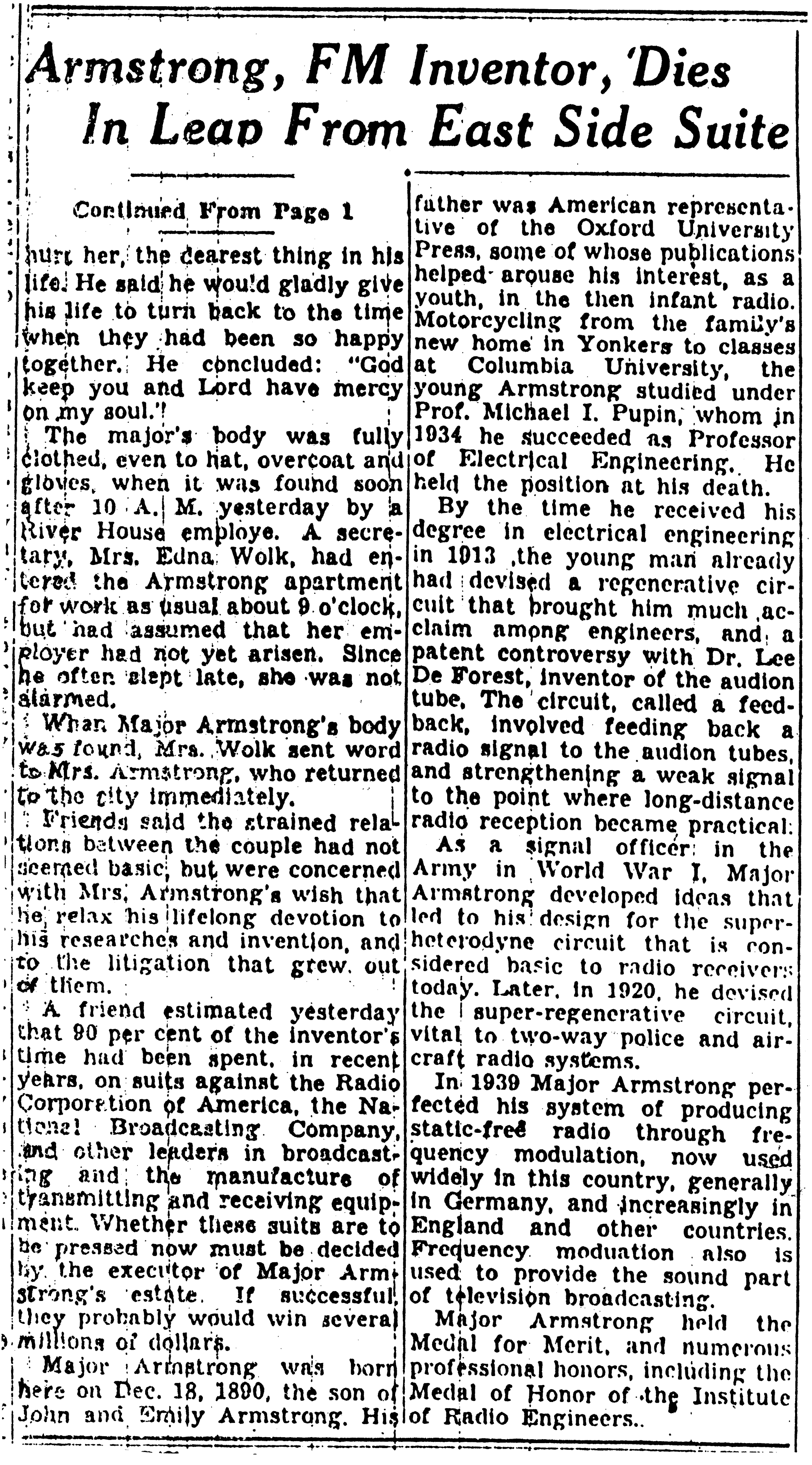
A two-page note, a penciled farewell to his wife, was found in the apartment. Dr. Emanuel Neuren, assistant medical examiner, listed the case as a suicide.

According to detectives of the East Fifty-first Street station, Major Armstrong had been alone after about 1 P. M. on Sunday. Mrs. Armstrong had been with a sister, Mrs. Marjorie Tuttle, in Granby, Conn., for a number of weeks. Three servants had gone out after serving lunch to the inventor Sunday afternoon.

Maj. Edwin H. Armstrong

In his message to his wife, the former Miss Marian MacInnis, Major Armstrong said that he was heartbroken at being unable to see her once again, and expressed deep regret at having

Continued on Page 13, Column 2



Armstrong, FM Inventor, Dies In Leap From East Side Suite

Continued From Page 1

hurt her, the dearest thing in his life. He said he would gladly give his life to turn back to the time when they had been so happy together. He concluded: "God keep you and Lord have mercy on my soul."

The major's body was fully clothed, even to hat, overcoat and gloves, when it was found soon after 10 A. M. yesterday by a River House employe. A secretary, Mrs. Edna Wolk, had entered the Armstrong apartment for work as usual about 9 o'clock, but had assumed that her employer had not yet arisen. Since he often slept late, she was not alarmed.

When Major Armstrong's body was found, Mrs. Wolk sent word to Mrs. Armstrong, who returned to the city immediately.

Friends said the strained relations between the couple had not seemed basic, but were concerned with Mrs. Armstrong's wish that he relax his lifelong devotion to his researches and invention, and to the litigation that grew out of them.

A friend estimated yesterday that 90 per cent of the inventor's time had been spent, in recent years, on suits against the Radio Corporation of America, the National Broadcasting Company, and other leaders in broadcasting and the manufacture of transmitting and receiving equipment. Whether these suits are to be pressed now must be decided by the executor of Major Armstrong's estate. If successful, they probably would win several millions of dollars.

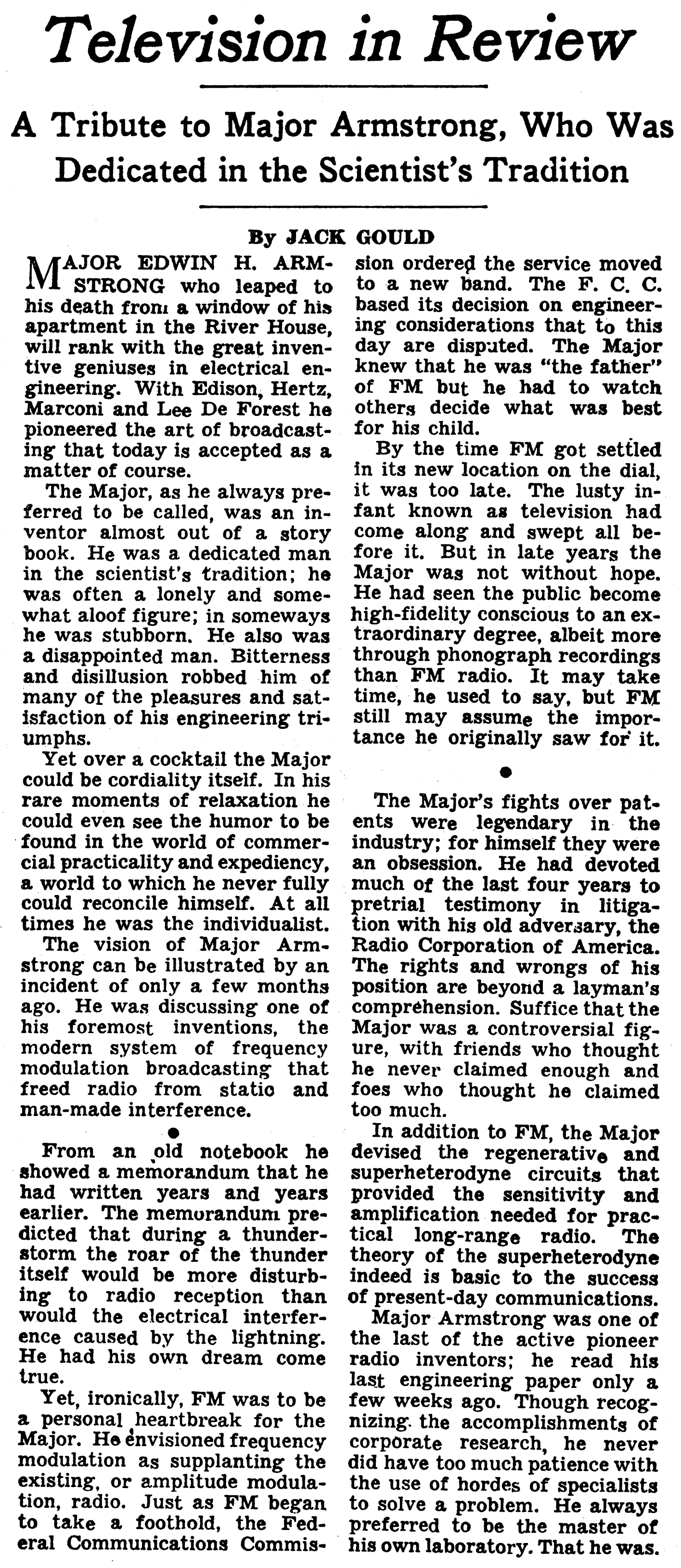
Major Armstrong was born here on Dec. 18, 1890, the son of John and Emily Armstrong. His father was American representative of the Oxford University Press, some of whose publications helped arouse his interest, as a youth, in the then infant radio. Motorcycling from the family's new home in Yonkers to classes at Columbia University, the young Armstrong studied under Prof. Michael I. Pupin, whom in 1934 he succeeded as Professor of Electrical Engineering. He held the position at his death.

By the time he received his degree in electrical engineering in 1913 ,the young man already had devised a regenerative circuit that brought him much acclaim among engineers, and a patent controversy with Dr. Lee De Forest, inventor of the audion tube. The circuit, called a feedback, involved feeding back a radio signal to the audion tubes, and strengthening a weak signal to the point where long-distance radio reception became practical.

As a signal officer in the Army in World War I, Major Armstrong developed ideas that led to his design for the superheterodyne circuit that is considered basic to radio receivers today. Later, in 1920, he devised the super-regenerative circuit, vital to two-way police and aircraft radio systems.

In 1939 Major Armstrong perfected his system of producing static-free radio through frequency modulation, now used widely in this country, generally in Germany, and increasingly in England and other countries. Frequency moduation also is used to provide the sound part of television broadcasting.

Major Armstrong held the Medal for Merit, and numerous professional honors, including the Medal of Honor of the Institute of Radio Engineers.



Television in Review

A Tribute to Major Armstrong, Who Was Dedicated in the Scientist's Tradition

By JACK GOULD

MAJOR EDWIN H. ARMSTRONG who leaped to his death from a window of his apartment in the River House, will rank with the great inventive geniuses in electrical engineering. With Edison, Hertz, Marconi and Lee De Forest he pioneered the art of broadcasting that today is accepted as a matter of course.

The Major, as he always preferred to be called, was an inventor almost out of a story book. He was a dedicated man in the scientist's tradition; he was often a lonely and somewhat aloof figure; in someways he was stubborn. He also was a disappointed man. Bitterness and disillusion robbed him of many of the pleasures and satisfaction of his engineering triumphs.

Yet over a cocktail the Major could be cordiality itself. In his rare moments of relaxation he could even see the humor to be found in the world of commercial practicality and expediency, a world to which he never fully could reconcile himself. At all times he was the individualist.

The vision of Major Armstrong can be illustrated by an incident of only a few months ago. He was discussing one of his foremost inventions, the modern system of frequency modulation broadcasting that freed radio from static and man-made interference.

●

From an old notebook he showed a memorandum that he had written years and years earlier. The memorandum predicted that during a thunderstorm the roar of the thunder itself would be more disturbing to radio reception than would the electrical interference caused by the lightning. He had his own dream come true.

Yet, ironically, FM was to be a personal heartbreak for the Major. He envisioned frequency modulation as supplanting the existing, or amplitude modulation, radio. Just as FM began to take a foothold, the Federal Communications Commission ordered the service moved to a new band. The F. C. C. based its decision on engineering considerations that to this day are disputed. The Major knew that he was "the father" of FM but he had to watch others decide what was best for his child.

By the time FM got settled in its new location on the dial, it was too late. The lusty infant known as television had come along and swept all before it. But in late years the Major was not without hope. He had seen the public become high-fidelity conscious to an extraordinary degree, albeit more through phonograph recordings than FM radio. It may take time, he used to say, but FM still may assume the importance he originally saw for it.

●

The Major's fights over patents were legendary in the industry; for himself they were an obsession. He had devoted much of the last four years to pretrial testimony in litigation with his old adversary, the Radio Corporation of America. The rights and wrongs of his position are beyond a layman's comprehension. Suffice that the Major was a controversial figure, with friends who thought he never claimed enough and foes who thought he claimed too much.

In addition to FM, the Major devised the regenerative and superheterodyne circuits that provided the sensitivity and amplification needed for practical long-range radio. The theory of the superheterodyne indeed is basic to the success of present-day communications.

Major Armstrong was one of the last of the active pioneer radio inventors; he read his last engineering paper only a few weeks ago. Though recognizing the accomplishments of corporate research, he never did have too much patience with the use of hordes of specialists to solve a problem. He always preferred to be the master of his own laboratory. That he was.

New York Times, February 4, 1954.

WIRELESS
ENGINEER

Vol. 31 MARCH 1954 No. 3

Edwin H. Armstrong

By his death on 1st February the United States lost one of the outstanding personalities of the wireless world. Edwin Howard Armstrong was born in New York on 18th December 1890. He graduated in Electrical Engineering at Columbia University in 1913 and was awarded an honorary D.Sc. in 1929. He was an assistant in the electrical engineering department for a year after graduation, and then for 21 years collaborated with Michael Pupin in research at the Marcellus Hartley Research Laboratories in Columbia University. From 1934 until his death he was a Professor of Electrical Engineering in the University. During the first world war he spent two years, first as captain and then as major, in the Signal Corps, and in 1919 was made a Chevalier of the Légion d'Honneur.

The name of Armstrong is most closely associated with four inventions, viz. the regenerative circuit, 1912; the superheterodyne system of reception, 1917-18; the superregenerative circuit, 1920; and frequency modulation, 1935. He was a lad of 16 when in 1906 Lee de Forest patented the 3-electrode valve, which became known as the audion, and it was in 1912, while still a student at Columbia, that he was experimenting with an audion when he discovered the presence of h.f. current in the anode circuit, which led to his invention of regeneration and the valve oscillator, and endless patent litigation. In 1914 he published a correct explanation of the action of a triode and disproved some of the currently-accepted ideas; in 1915 he read a paper on regeneration before the Institute of Radio Engineers, and in 1916 another paper on the heterodyne detector. The impact of these papers may be judged from the fact that in the following year the Institute of Radio Engineers awarded him the first Medal of Honour for his work on regeneration and the production of oscillations. Seventeen years later there was a somewhat tragic sequel to this award for, following the adverse decision of the U.S. Supreme Court on the question of priority of invention of these discoveries, he returned the medal to the Institute in 1934. The Board of Directors, however, unanimously declined to accept it and reaffirmed the original award.

Though naturally not entirely unbiased, some light is thrown on this long drawn-out litigation by the autobiography of Lee de Forest, published in 1950. At the same time as Armstrong was experimenting with the audion in New York, Lee de Forest and two assistants were working on somewhat similar lines at Palo Alto in California, and the fight as to who was the prior inventor went on for 20 years.

In the autumn of 1913 de Forest read a paper on "The Audion Amplifier" before the I.R.E. at Columbia University and he says: "My demonstration of the crashing sounds emitted from my loudspeaker when I dropped a handkerchief on the table before the telephone receiver serving as my 'pick-up' aroused great astonishment and applause. On that occasion young Edwin H. Armstrong, wrapped in deepest mystery, had a small carefully-concealed box in an adjoining room into which neither I nor my assistant Logwood was permitted to peek. But when he led two wires to my amplifier input to demonstrate

This article on Armstrong appeared in the Wireless Engineer of March 1954. It was written by the Technical Editor Prof. G. W. O. Howe.

the squeals and whistles and signals he was receiving from some transmitter down the Bay, we thought we had a pretty fair idea of what the young inventor had concealed in his box of mystery. So we proceeded, meekly and obediently, to amplify whatever signals came over the wires from that room".

That is the first mention of Armstrong in de Forest's autobiography, but early in 1914 de Forest demonstrated his ultra-audion oscillator at the Bureau of Standards in Washington, and he says that Professor Pupin, whom he had long known as a kindly friend, loudly demanded "What right have you to have that here? That thing is not yours. That belongs to Armstrong." He says that he was too flabbergasted to reply, but gazed upon his surprising wrath and "continued the siren sounds." He proceeds, "Then I knew for a certainty what it was that Armstrong had had in his little magic box at Columbia. And that outburst by Professor Pupin was the opening gun of the bitterly contested patent battle to be waged for years in the Patent Office interference proceedings; and thereafter for years more until at long last the U.S. Supreme Court should finally decide the historic contest." Later de Forest says: "On January 15, 1920, I read my paper on the Audion and its evolution before the Franklin Institute at Philadelphia. It was well received, except by one E. H. Armstrong, who sought to show that it was he who had invented the feed-back circuit. 'All de Forest invented was the Audion! We'll concede that', he growled. Whereupon the chairman ordered him to sit down."

The feedback patent, which, after nearly 20 years' litigation, was finally awarded to de Forest, expired in 1941. It had been in turn awarded to Armstrong, then Langmuir, then again to Armstrong, and finally to de Forest. One can appreciate the feelings that prompted Armstrong to return the medal to the Institute.

Another of Armstrong's inventions, with much happier associations, is frequency modulation. This occurred to him as the result of some experiments he and Pupin made with the idea of eliminating static interference; experiments which, he says, were unsuccessful, but which laid the foundations of his system of reducing disturbance by using frequency modulation. In an outline of the history of f.m., which he gave before a section of the I.R.E. in 1946, he said that he started looking for a static eliminator back about 1914, and that he worked a little longer than most people did. He then hit upon the idea of frequency-shift keying and from that went on to frequency modulation. It is pleasing to note that towards the end of his autobiography de Forest says: "Major E. H. Armstrong deserves the greatest credit for the development of his system of frequency-modulation—brought out in spite of the skepticism of the profession, and a reluctant Federal Communications Commission. He has given to radio broadcasting a new arm; for this I salute him."

In 1935 the Radio Club of America founded a medal to be known as the Armstrong Medal. In 1941 Armstrong was awarded the Franklin Medal by the Franklin Institute, and in 1943 the Edison Medal by the American I.E.E.; he was also awarded medals by many other institutions.

In 1947 he received a Medal of Merit and a Presidential Citation for his contributions to military radio communications.

In "Radio: Beam and Broadcast", by A. H. Morse, published in 1925, the patent litigation up to that time is discussed very fully: the author concludes by saying that, "Armstrong's work in radio is such that, had he no patented or patentable inventions—and he has many—he would still rank as one of the foremost exponents of the art". This was before the invention of frequency modulation.

Since 1948 he had been working on what he called the multiplexed transmission of frequency-modulated signals, and as recently as last October he and J. S. Bose, also of Columbia University, read a paper on the subject and gave demonstrations before the Radio Club of America. The multiplex system enables two programmes to be broadcast simultaneously within the standard f.m. band of 200 kc/s. Earlier attempts at multiplexing were not very successful because of cross-modulation between the main and the auxiliary channel and of noise transfer from one to the other, but as the result of five years of work they claimed to have overcome the difficulties, and to be able to obtain results on their second or auxiliary channel superior to those obtained by ordinary amplitude-modulated stations.

One can only regret that so much of his life was overshadowed and embittered by such protracted patent litigation, but during the last 18 years he had the great satisfaction of seeing his frequency modulation becoming more and more highly appreciated, and replacing amplitude modulation on an increasing scale. His name will ever be associated with this outstanding achievement.

G. W. O. H.

OBITUARY - EDWIN HOWARD ARMSTRONG

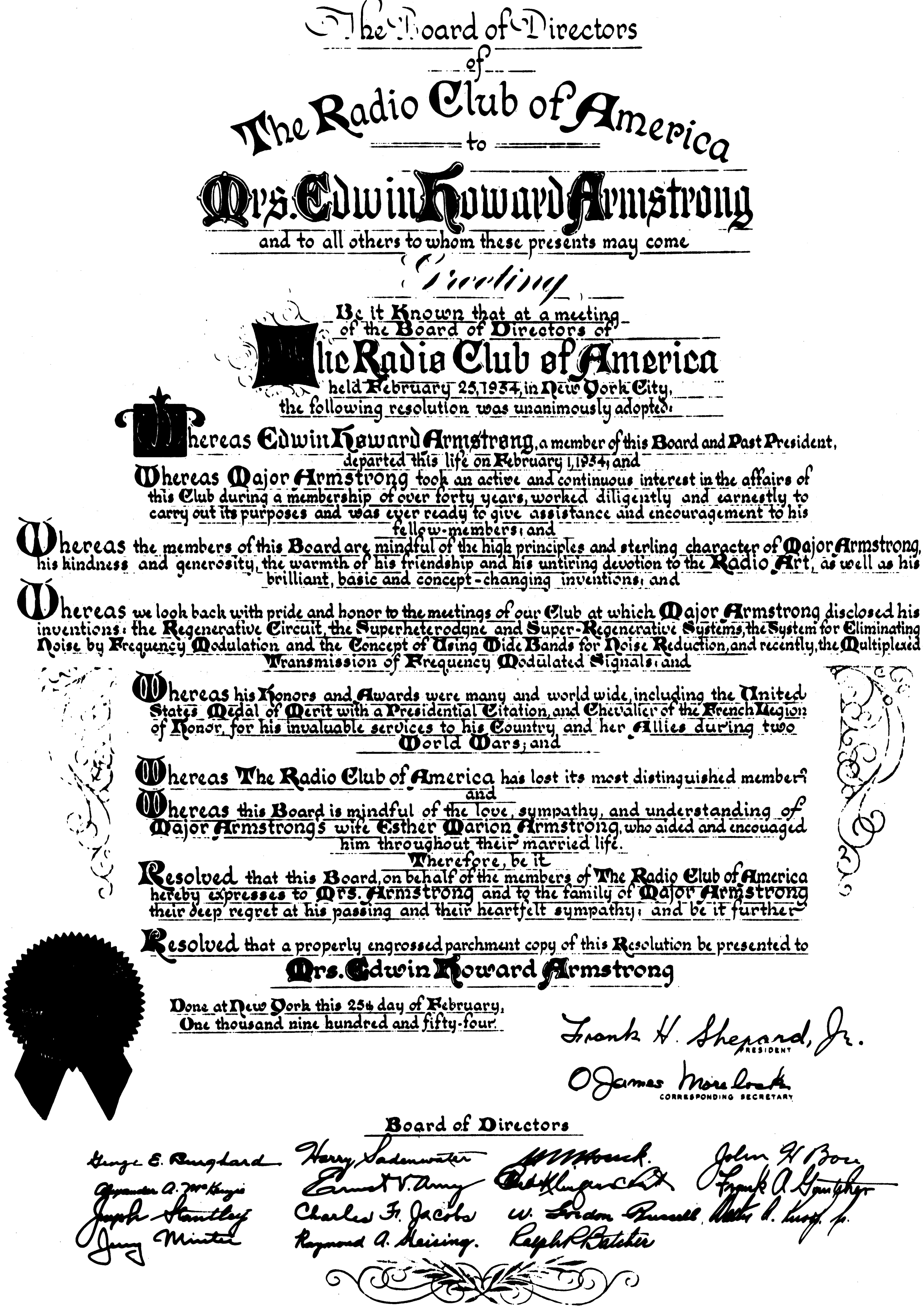
Originally published in the *PROCEEDINGS OF THE I.R.E.* Vol. 42, no. 3, March, 1954, p. 635

Major Edwin H. Armstrong (A '14, F '27), the inventor of frequency modulation and one of the leaders in radio development, died recently.

Major Armstrong was born in New York City on December 18, 1890. He entered Columbia University in 1909, and in 1913 he received his Bachelor's degree in Electrical Engineering. He remained at Columbia as an assistant in the Department of Electrical Engineering for one year. In 1915, he received the Trowbridge Fellowship at Columbia, and continued his work, begun in 1914, with Professor Michael I. Pupin at the Marcellus Hartley Research Laboratory. From 1917 - 1919 he served in the A.E.F. with the Signal Corps. He received the degree of Doctor of Science from Columbia University in 1929, and became Professor of Electrical Engineering at that Institution in 1937, continuing in this post until his death.

Major Armstrong was the inventor of four of the most important processes in radio development. In 1913 he invented the regenerative circuit, a development which made possible loud-speaker reception. In 1918, while serving with the Signal Corps, he developed the superheterodyne receiver circuit, which is used universally in ordinary radio receivers. The super-regenerative receiver circuit, which he invented in 1920, provided even greater amplification and made high-frequency short wave much more effective. As early as 1914 he began looking for a static eliminator, and by 1933 his experiments led him to the invention of the system of frequency modulation which eliminated electrical disturbances and brought about a marked increase in radio stations. His most recent work was in the development of a system of multiplexing FM so that more than one program could be sent out simultaneously on the same wavelength.

Major Armstrong had published many technical articles in the *Proceedings of the I.R.E.* and other professional journals. He was the recipient of a Presidential citation for his contribution to military communications, and in 1919 was made a Chevalier de la Legion d'Honneur. His other honors included: the first Medal of Honor of the IRE, awarded in 1917; the Egleston Medal, Columbia University, 1939; the "Model Pioneer" Plaque, National Association of Manufacturers, 1940; the Holley Medal, American Society of Mechanical Engineers, 1940; the Franklin Medal, Franklin Institute, 1941; the John Scott Medal, Board of City Trusts, City of Philadelphia, 1941; the first Armstrong Medal from the Radio Club of America, 1935; and the Medal for Merit, 1947.



The Board of Directors

of

The Radio Club of America

to

Mrs. Edwin Howard Armstrong

and to all others to whom these presents may come

Greeting

Be it Known that at a meeting of the Board of Directors of **The Radio Club of America** held February 25, 1954, in New York City, the following resolution was unanimously adopted:

Whereas Edwin Howard Armstrong, a member of this Board and Past President, departed this life on February 1, 1954, and

Whereas Major Armstrong took an active and continuous interest in the affairs of this Club during a membership of over forty years, worked diligently and earnestly to carry out its purposes and was ever ready to give assistance and encouragement to his fellow-members; and

Whereas the members of this Board are mindful of the high principles and sterling character of Major Armstrong, his kindness and generosity, the warmth of his friendship and his untiring devotion to the Radio Art, as well as his brilliant, basic and concept-changing inventions; and

Whereas we look back with pride and honor to the meetings of our Club at which Major Armstrong disclosed his inventions: the Regenerative Circuit, the Superheterodyne and Super-Regenerative Systems, the System for Eliminating Noise by Frequency Modulation and the Concept of Using Wide Bands for Noise Reduction, and recently, the Multiplexed Transmission of Frequency Modulated Signals; and

Whereas his Honors and Awards were many and world wide, including the United States Medal of Merit with a Presidential Citation, and Chevalier of the French Legion of Honor, for his invaluable services to his Country and her Allies during two World Wars; and

Whereas The Radio Club of America has lost its most distinguished member; and

Whereas this Board is mindful of the love, sympathy, and understanding of Major Armstrong's wife Esther Marion Armstrong, who aided and encouaged him throughout their married life.

Therefore, be it

Resolved that this Board, on behalf of the members of The Radio Club of America hereby expresses to Mrs. Armstrong and to the family of Major Armstrong their deep regret at his passing and their heartfelt sympathy; and be it further

Resolved that a properly engrossed parchment copy of this Resolution be presented to

Mrs. Edwin Howard Armstrong

Done at New York this 25th day of February,
One thousand nine hundred and fifty-four.

Frank H. Shepard, Jr.
PRESIDENT

O. James Morelock
CORRESPONDING SECRETARY

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From the prayer read in Armstrong's memory at the Club's 1954 Annual Meeting:

"He will long be remembered in the world of science, and students of the future will learn of his great contributions to the Radio Art. Those of us who were close to him know, that whether in the laboratory or in the field, he was always ready and willing to share his knowledge and experience.

His contributions to the radio industry had a a profound effect upon the lives of most of us present here tonight -- yes, even upon our nation and on and the rest of the free world's successful defense of liberty during the last two World Wars.

It is for us, his friends, to remember how he enriched the lives of all associated with him."